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SEASONAL PATTERN OF SOIL QUALITY, SOIL WATER AND THERMAL REGIMES AND PERFORMANCE OF BIOFUEL CROPS UNDER DIFFERENT MANAGEMENT PRACTICES

TESE DE DOUTORADO

Gabriel Oladele Awe

Santa Maria, RS, Brasil

2014

SEASONAL PATTERN OF SOIL QUALITY, SOIL WATER AND THERMAL REGIMES AND PERFORMANCE OF BIOFUEL CROPS UNDER DIFFERENT MANAGEMENT PRACTICES

Gabriel Oladele Awe

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elaborada por
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DEDICATION

I dedicate this program to God Almighty, **the Alpha and Omega**, and to my beloved parent, my father, **Chief Julius Olusegun Awe**, of blessed memory and my mother, **Chief (Mrs.) Victoria Bosede Awe**, for their tireless effort to ensure that I get to this level.

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Gabriel Awe
2014

RESUMO

Tese de Doutorado
Programa de Pós-Graduação em Ciência do Solo
Universidade Federal de Santa Maria

PADRÃO SAZONAL DA QUALIDADE DO SOLO, ÁGUA, REGIMES TÉRMICOS E DESEMPENHO DE CULTURAS PARA BIOCOMBUSTÍVEIS SOB DIFERENTES PRÁTICAS DE MANEJO

AUTOR: GABRIEL OLADELE AWE
ORIENTADOR: JOSÉ MIGUEL REICHERT
Local e Data: Santa Maria, 15 de Setembro de 2014.

A intensificação da produção de biocombustíveis pode prejudicar a qualidade do solo. Portanto, para evitar a degradação do solo é necessário monitorar periodicamente os atributos mais afetados pela atividade agrícola. Assim, o objetivo deste estudo foi investigar o padrão sazonal da qualidade, da água e regimes térmicos do solo, bem como o desempenho das culturas da cana-de-açúcar e do tungue na estação experimental do Departamento de Solos da Universidade Federal de Santa Maria, Santa Maria, RS, Brasil. Para isso foram avaliados dois experimentos. O experimento de cana-de-açúcar (três anos de cultivo) foi implantado em 2010 e os tratamentos foram: plantio direto; plantio direto com compactação adicional; preparo convencional e; escarificado, distribuídos em um delineamento de blocos casualizados com três repetições. Nos anos de 2011 e 2012, não houve revolvimento do solo, mas foi adicionada cobertura vegetal morta, designando um esquema de parcelas subdivididas. Para o sistema de cultivo do tungue (dois anos de cultivo, 2012-2014) foi utilizado um experimento de blocos ao acaso com quatro repetições. Os tratamentos foram: tungue-crambe-girassol / soja com fertilizantes inorgânicos; tungue-crambe-girassol / soja com adubação orgânica; tungue-aveia-amendoim; e tungue (controle). Crambe e aveia foram plantadas no inverno, enquanto girassol (1° ano) / soja (2º ano) e amendoim foram plantados no verão. Amostras de solo com estrutura alterada e preservada foram coletadas (usando cilindros com 57 mm de diâmetro e 40 mm de altura) nas camadas de 0-10, 10-20, 20-40 e 40-60 cm na cana-de-açúcar, e de 0-10, 10-20, 20-40, 40-60 e 60-80 cm no tungue para a determinação laboratorial dos indicadores de qualidade do solo. Houve o monitoramento á campo da temperatura, umidade potencial matricial da água no solo e parâmetros agronômicos incluindo a produtividade da cana-de-açúcar e altura da planta de tungue. Um conjunto mínimo de dados para a avaliação da qualidade do solo foi obtido através da análise de componentes principais e o índice de qualidade do solo foi obtido pelo método aditivo ponderado. Os padrões temporais de armazenamento de água do solo e a temperatura do solo foram avaliados utilizando algoritmos para dados de séries temporais. Exceto para a macroporosidade, na camada de 0-10 cm dos tratamentos com preparo do solo, o preparo e a cobertura de palha não afetaram significativamente ($p < 0{,}05$) os indicadores de qualidade do solo, o índice de qualidade do solo, a retenção de água ou a produtividade de cana-de-açúcar. O grau de compactação não foi suficiente para limitar o crescimento da cana-de-açúcar. A permanência da palha na superfície influenciou significativamente os processos temporais de temperatura do solo e a análise temporal foi melhor do que a análise de regressão clássica para a análise das séries temporais de armazenamento de água e temperatura do solo. O sistema de cultivo não influenciou significativamente ($p<0{,}05$) os indicadores de qualidade do solo, o índice de qualidade do solo e a altura da planta, mas influenciou significativamente a retenção de água do solo. Nos dois experimentos, não houve nenhuma tendência clara nos valores sazonais de variáveis físico-hídricas do solo e na resposta da cultura.

Palavras chave: Preparo do solo, cobertura vegetal, sistema de cultivo, índice de qualidade do solo, retenção de água no solo, desempenho da cultura, análise de séries temporais.

ABSTRACT

Doctoral Thesis
Post Graduate Program in Soil Science
Federal University of Santa Maria, Brazil

SEASONAL PATTERN OF SOIL QUALITY, SOIL WATER AND THERMAL REGIMES AND PERFORMANCE OF BIOFUEL CROPS UNDER DIFFERENT MANAGEMENT PRACTICES

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ADVISER: JOSÉ MIGUEL REICHERT
Place and date: Santa Maria, September 15, 2014.

The intensification of biofuel production causes negative impacts on soil quality, thus the soil requires adequate assessment to ascertain its quality status, however site-specific nature of results in literature requires independent soil property measurement and assessment depending on specific agroecosystem and management goals. Therefore, the main objective of this study was to investigate seasonal pattern of soil quality, soil water and thermal regimes and performance of sugarcane and tung crops at the experimental station of Soils Department, Federal University of Santa Maria, Santa Maria, RS, Brazil. The sugarcane experiment (three seasons) was established in 2010 under no-tillage; no-tillage + compaction; conventional tillage and chiseling treatments in a randomized complete block design with three replications. In years 2011 and 2012, there was no soil disturbance; however residue mulching was imposed, giving split-plot design. The tung-based cropping system (two seasons, 2012-2014) was a randomized complete block design experiment with four replications. The treatments were: tung-crambe-sunflower/soybean + inorganic fertilizer; tung-crambe-sunflower/soybean + organic manure; tung-oats-peanut; and sole tung (control). Crambe and oats were planted in winter while sunflower (1st year)/soybean (2nd year) and peanut were planted in summer. Disturbed and undisturbed (using cores of known volume) soil samples were collected from soil layers 0-10, 10-20, 20-40 and 40-60 cm in sugarcane, and 0-10, 10-20, 20-40, 40-60 and 60-80 cm in tung for the laboratory determination of soil quality indicators. There was field monitoring of soil water retention, matric potential and soil temperature and agronomic parameters measured include sugarcane yield and tung plant height. Minimum data set for soil quality assessment was made using principal component analysis and soil quality index was obtained using weighted additive method. The temporal patterns of soil water storage and temperature were evaluated using algorithms for time series data. Except for Ma in 0-10 cm layer of tillage plots, both tillage and residue mulching did not significantly affect ($p<0.05$) the soil quality indicators, overall soil quality, water retention and sugarcane yield. The degree of compaction was not enough to limit sugarcane growth. Residue retention significantly influenced temporal processes of soil temperature and state-time analysis was better than classical regression of time series analysis of soil water storage and temperature. Cropping system did not significantly influence ($p<0.05$) soil quality indicators, overall SQI and tung plant height, but significant influenced soil water retention. For the two experiments, there was no discernible trend in the seasonal values of soil hydro-physical variables and crop response.

Keywords: Soil tillage, residue mulching, cropping system, soil quality index, soil water retention, crop performance, time series analysis.

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1 INTRODUTION

Biofuel production is now an integral part of economy of most developed countries and under different stages of adoption in various developing economies due to the depleting fossil fuel reserve, global energy security strategies and environmental pollution (IEA, 2008). In this context, many countries have mandated the use of biofuels and are heavily investing in its research, development, and production (FAO, 2008),with great clamour to integrate the production of these valuable plants into farming systems both in developed and developing nations (CARBALLO et al., 2008). However, there is still the question of sustainability regarding the intensification of biofuel crop production and other crops to meet food security aspect of the millennium development goals (MGDs) as these measure could perturb the environmental balance, mostly soil quality, largely because of shifts in land use (MANDAL et al., 2013) and effect of management(SHARMA et al., 2008).

Soil quality is the basis for the development of agricultural sustainability (DORAN and ZEISS, 2000), serving as an indicator for land use (TESFAHUNEGN, 2014), soil and crops management (MANDAL et al., 2013), indicating that the relationship between SQ and agricultural sustainability is contained in the production of food and fiber in the soil's capability of fulfilling its function in a manner, economically viable, environmentally safe and socially acceptable. Therefore, sustainable cropping requires knowledge of the impact of agricultural practices on soil quality. In this context, the need for understanding and assessing soil quality has increased as soil is a vital component of the Earth's biosphere, functioning not only in the production of food and fibers, but also in the maintenance of environmental quality (GLANZ, 1995).Soil scientists, farmers and government institutions are interested in obtaining soil quality (SQ) indicators to evaluate the land in relation to degradation, estimate research needs and funding and judge management practices in order to monitor changes in soil properties and processes, sustainability of the soil resource base and environmental quality that occur over time in response to land use and management practices (KARLEN et al., 2001). However, there is still controversy on what constitutes a good soil as a result of individual priority with respect to soil function, intended land use, cultural practices and the interest of the end users (DORAN and PARKIN, 1994). Nevertheless, soil quality assessment has become a decision tool that helps organize soil information, interpret how management practices affect soils and effectively combine a variety of information for multi-objective decision-making to identify management choices with the fewest consequences to reduce environmental degradation (MANDAL et al., YAO et al., 2013).

Soil management highly influences soil properties and processes. According to Alletto and Coquet (2009), soil and crop management are the principal agents causing the modification of soil structural state on which various soil properties are dependent and when these actions are applied, they have their transient effects manifested at different time scales. Although soil tillage produces a suitable tilth for crop growth by temporarily decreasing bulk density and increasing the volume of macropores (LOGSON et al., 1990), modifies soil thermal regime (ANDRADE et al., 2010) but with time, it increases soil bulk density, decreases porosity and soil available water capacity (FRANZLUEBBERS, 2002), and lead to loss of soil organic matter (Al-KAISI and YIN, 2005) as a result of reconsolidation of the soil caused by alternative wetting and drying cycles either by rain events or irrigation (GREEN et al., 2003) during the crop growing cycle, depending on soil texture. Thus, tillage distorts the soil matrix and modifies the structure (STRUDLEY et al., 2008), resulting in variability in the dynamics of the unstable soil physical and hydraulic properties (BAMBERG et al., 2011). The reconsolidation of the soil is a dynamic process, depending on the frequency (CAMEIRA et al., 2003), amount (BANDARANAYAKE and ARSHAD, 2006) and methods (BANDARANAYAKE et al., 1998) of water application and subsequent drying process.

The use of soil conservation practices such as retention of crop residue of previous harvest has been promoted. Crop residue retention on the soil surface is a conservation management practice aimed at better management of water, improving aggregation and porosity and control of erosion (JORDAN et al., 2010). Duiker and Lal (2000) states that residue mulching, apart from enhancing soil quality, possesses the potential to increase infiltration and mitigate evaporative losses. Positive effects of residue mulching on soil quality indicators (BLANCO-CANQUI and LAL, 2007b), water retention (CAMILOTTI et al., 2005) and suppression or increasing of extreme soil thermal regimes (ERUOLA, 2012) have been documented, although results are not the same across different soils and climatic regions.

Agroforestry or alley cropping is a land use system whereby trees are grown in association with other annual, early maturing or perennial crops and/or cattle in predetermined spatial and time arrangements, using management practices that are compatible with the local setting, resulting in ecological and economic interactions between the trees and other crops. Agroforestry possesses some advantages such as soil organic carbon build up (MUTUO, 2005), reduction in frequency of land abandonment through improved soil quality (PARROTTA et al., 1997), promotes environmental sustainability and economic benefits to rural farmers (GARRITY, 2004) in comparison to other agricultural systems. According to Massimo and Marco (2003), comparing with high-input mono-cropping systems, intercropping could promote more long-term returns, improve resource-use efficiency and reduce erosion on steep lands, and has become sustainable soil management system in many developing and developed economies. However, competition for resource use such as light, nutrients and water weakened the adoption of agroforestry systems, especially in the arid and semi-arid regions (ONG et al., 1996).

Crop productivity integrates all the complex and dynamic soil properties and processes. Soil properties and processes are often perturbed by management practices, thus influencing crop growth and yield. The results of the effects of soil microclimatic modification by soil and crop management practices on crop yield have remained contradictory (AGBEDE, 2006; ODJUGO, 2008; OLIVER and SINGELS, 2006; MOHAMMAD et al., 2012), thus interpretations are quite confusing.

Among soil properties, soil water retention is the most important state variable in hydrologic and biological processes (CHOI and JACOBS, 2007). In the superficial layer, soil moisture plays a significant role in water dynamics and energy flow (VEREECKEN et al., 2007), controls the partitioning of precipitation (PACHEPSKY et al., 2003) into infiltration and surface runoff, which are important components of the soil water balance. Soil moisture is very important in crop production. Of the four physical conditions (water, temperature, aeration and mechanical resistance) directly related to plant growth, water is the dominant controlling factor as others are affected by water content (LETEY, 1985). Knowledge of soil water storage and dynamics is therefore very vital for rational management of any soil and crop, besides enabling the prediction of several hydrologic processes (WESTERN et al., 2004) as well as giving information on environmental aspects of the water cycle (TIMM et al., 2011).

Soil temperature is a dynamic soil property as it changes with climatic variability and other processes such as soil management (ANDRADE et al., 2010). Any practice or process which tends to cause soil compaction, such as tillage, will increase bulk density and reduce porosity, with a significant effect on soil water and temperature dynamics. The effect of tillage and residue mulching on soil thermal regime has been studied (e.g. ODJUGO et al., 2008) but results are not the same because of varying soil types, climate and cultural practices.

For years, traditional classical statistical analysis of variance or multiple regressions have been the main tools for analyzing field data. These studies normally neglected the influence of spatial and temporal heterogeneity of field soils and weather conditions, respectively, ignoring the facts that observations are also spatially or temporally independent of each other and that mean values are based on normally distributed sets of measurements (NIELSEN and WENDROTH, 2003). In this context, Nielsen and Alemi (1989) affirm that observations conducted limited to the traditional classical statistics have yielded to results between and within treatments which are not always independent, making it impossible to apply in another place or different scenario. Based on this weakness, soil scientists, environmental engineers and hydrologists are now complementing field evaluations with other statistical tools and approaches such as geostatistics, neural networks and state-space (time) to examine data observed at different points or periods with a view to understanding the structure of spatial and temporal distribution of soil-plant-atmospheric processes at different scales (WESTERN et al., 2002; TIMM et al., 2006; HU et al., 2008). Therefore understanding the temporal process of variables observed over time could be useful tool for modeling and decision making.

1.1 Justification

The search for indicators to assess soil structural quality has been an intriguing task for research in recent years, due to the complex soil-plant interaction. These indicators have been based on direct and indirect factors of plant growth, for example, soil water availability and aeration, or physical properties such as the soil bulk density, porosity and hydraulic conductivity, which may be specific properties or dynamic processes in nature, making it difficult to relate changes in these direct and indirect factors of plant growth to crop production because of, climatic condition, seasonal variation and variable soil and crop parameters. There are many studies in the literature highlighting the long-term effects of tillage on soil physical and hydraulic properties (eg LIEBIG et al., 2004) but less work is available on seasonal variability of soil properties under different management practices (JIRKU et al., 2010). Soil quality as affected by management practices has been a subject of research (AZIZ et al., 2011; GILLEY et al., 1997; IMAZ et al., 2010; JACKSON et al., 2003;

LEE et al., 2006; MANDAL et al, 2013), however there is dearth of information on soil quality status of soil grown to sugarcane under different soil management practices.

In Brazil and elsewhere, farmers have grown tung oil crop for years and cultivated annual and early-maturing crops as intercrops either at the early stage of establishment or permanent agroforestry system with aims such soil and water conservation, alternative food and biofuel production before the maturation of main plant, increase yield etc, however, information on the quality status of tung soil environment and its performance in agroforestry system is not documented till today. Apart from reports on its growth, uses and medicinal attributes, no or limited attempt, if any, has been made to evaluate the soil environment where it grows. Therefore, research is needed to characterize the soil physical, chemical and biological properties of the tung soil environment as well as the soil quality status under the agroforestry system to better understand the relationship between soil properties and tung growth.

Despite quantum of studies on spatial analysis of soil water content/storage and temperature at different scales, limited study has considered the time series analysis of these soil variables monitored over time as well as the influence of management on their temporal processes. Therefore, effort in this direction could motivate the application in another region or other soil, plant, atmospheric variables measured over time.

1.2 Hypotheses

Based on the conclusions and justifications made above, this research seeks to test the following hypotheses:

(i) tillage and residue mulching significantly affect soil quality indicators, overall soil quality, water retention and yield of sugarcane over years.

(ii) there is significant interaction between tillage and residue mulching on soil quality indicators and sugarcane yield.

(iii) soil quality index, soil water retention and growth of tung oil tree are significantly higher in the tung-based agroforestry than in sole tung crop.

(iv) residue mulching significantly influence temporal processes of soil temperature.

(v) applied statistical time series analysis is significantly better than classical regression of time series analysis of soil water storage and temperature.

1.3 Objectives

1.3.1 General objective

The overall aim of this study was to investigate the effects of different management systems on seasonal pattern of soil quality status, water retention, and performance of (i) tillage-established sugarcane (*Saccharum Officinarum)* subjected to residue mulching and (ii) tung oil tree (*Aleurites moluccana (L.) Wild*) in a tung-based agroforestry system.

1.3.2 Specific objectives

The specific objectives were to:

(i) investigate seasonal pattern of soil quality indicators, water retention and yield of sugarcane established with different tillage methods and subjected to residue mulching.

(ii) evaluate seasonal pattern of soil quality status, soil water retention and growth of tung plant in a tung-based cropping system.

(iii) determine the effect of tillage and residue mulching on the temporal processes of temporal data of soil water storage and temperature.

(iv) evaluate the adequacy of applied statistical time series analysis of soil water storage and temperature of the sugarcane field compared with classical statistical regression.

2 LITERATURE REVIEW

2.1 Biofuel production

In an effort to reduce dependence on declining fossil fuels, reduce environmental pollution and enhance energy security, many countries are mandating the use of bioenergy and heavily investing in its research, development, and production. For example, the European Union established a directive on the use of renewable energy in 2008. They stipulated that 20% of the energy consumed by member states be derived from renewable sources, with biofuels providing at least 10% of all transportation fuels by 2020 (COMMISSION OF THE EUROPEAN COMMUNITIES, 2008). Similarly, other countries such as Brazil, China, and the USA have adopted aggressive bioenergy policies in recent years, resulting to the large-scale mechanization of sugarcane, cassava, jatropha and other energy crops such as tung, worldwide in efforts towards achieving targets and policies to promote significant biofuels production (DUFEY and GRIEG-GRAN, 2010).

As of 2010, 8.3 million ha (Mha) of biodiversity-rich tropical lowland forest in Malaysia had been converted to oil palm plantations to serve both food and biofuel markets (KOH et al., 2011), with biofuels predominantly driving this expansion in the past decade. In the same vein, Indonesia plans to double its production of oil palm by 2020 to meet European and East Asian demands (KOH and GHAZOUL, 2010).

Since 1975, Brazil began a large-scale program to produce biofuel to reduce dependency on oil imports. According to projections by the Brazilian Ministry of Agriculture, Livestock, and Food Supply (MAPA), it states that the country would soon become the leading world producer of biofuels (MAPA, 2008), given the possibility the amount of agro-energy crops cultivated can still be expanded, since over 91 million hectares of land are still available for agricultural expansion, provided the legal and normative requirements related to land use and occupation are strictly complied with (MAPA, 2007).

In the USA, the national biofuel policies are the partial cause of shifts from the traditional corn–soybean biennial crop rotation to corn–corn–soybean rotation or continuous corn cropping and the conversion of grasslands, including native prairies and other previously fragile and untilled areas (FARGIONE et al., 2009; BABCOCK and FABIOSA, 2011).

However, the environmental sustainability of the various soil and crop management techniques to achieve the increased biofuel production to meet demand has become a major

concern with soil structural quality and water availability as focal points in this context. The intensity of land use and larger, heavier and more sophisticated agricultural machinery (BERISSO et al., 2012), have altered the ecosystem functioning and increased the potential for soil compaction.

2.1.1 Sugarcane

The sugarcane (*Saccharum officinarum L.*) belongs to the grass family, *Poaceae*. The cultivation of sugarcane was reported to originate on the Island of New Guinea in the south Pacific around 6000BC. Sugarcane production spread along human migration routes to southeast Asia, India and the Pacific, hybridizing with wild sugarcanes to produce “thin” canes. It reached the Mediterranean between 600-1400 AD. From there it spread to Egypt, Syria, Crete Greece and Spain followed by introduction to West Africa and subsequently Central and South America and the West Indies, growing in a wide range of ecology and at diverse latitudes in the tropics through to the temperate climates (AUSTRALIA, 2008). Today, the major producers are Brazil, India, China, Australia, Thailand and Mexico.

With close to 7 Mha of agricultural land currently devoted to sugarcane production, Brazil is second only to the USA in bioethanol production, reaching about 19 billion liters in 2007 (MONTEIRO et al., 2010). Among the raw materials used to produce ethanol, sugarcane presents the highest yield and the lowest production costs to the country (MAPA, 2007). Sugarcane cropping is concentrated in the Center-South regions of the country and the state of São Paulo represents around 60% of the Brazilian sugarcane belt, occupying approximately 3.8 Mha (CONAB, 2008).

The expansion of sugarcane production has historically resulted in the direct clearing of the biodiversity-rich Cerrado (Savannah) and Atlantic forest habitats (SILVEIRA et al, 2003), and indirectly to deforestation of Amazonian forests through the displacement of soybean production and pasturelands (MARTINELLI and FILOSO, 2008). Sugarcane agribusiness in Brazil is an activity which has been responsible for the economic growth of a large number of municipalities, by contributing to empowerment in the rural areas and provides huge capacity to add value to the production. Furthermore, it is considered more favorable raw material for the production of biofuel because it has potential for reduction of 70 to 90% or more of the greenhouse gases (NGUYEN et al. 2007).

Although sugarcane is grown in the Rio Grande do Sul state, southern region of Brazil, the production has not been significant at the national level mainly because of the extreme cold normally experienced during the late growth stage which affects product quality, hence limited research involving sugarcane in this region. However, efforts are being made to introduce cold-resistance varieties to meet the agricultural capability of the state in the cultivation of sugarcane. In this context, nine new sugarcane cultivars have been developed, termed breaking the paradigm in the production of sugarcane, representing a symbolic milestone for the qualification of ethanol production in Rio Grande do Sul. Tests conducted on the new varieties gave medium and high productivity, regular conditions under stress from cold, good plant health, as well as rapid growth (NOTÍCIAS DO ESTADO DO RS, 2012). These findings are impetuous and opportunities for research in sugarcane in Rio Grande do Sul State as was not the case for years. In other regions too, research in sugarcane is limited to irrigation, with very few research focused on rainfed sugarcane production. Very important too is residue management. Despite the introduction of mechanical harvesters for sugarcane, a large proportion of farmers still practice the burn and harvest method, which is very detrimental to the environment, the soil in particular. Thus, research is needed on the effect of management systems on the soil environment, water retention and water use efficiency of rainfed sugarcane. Thus, information on application of various soil and crop management techniques on such soil environment will guide in defining appropriate technique to ensure optimum crop yield, adequate soil and water management and sustainable environment.

2.1.2 Tung

Tung (*Aleurites fordii Hemsl.),* belongs to the family, *Euphorbiaceae* and sub-family, *Crotonoideae*. It is one of the world’s great domesticated multipurpose trees, with large geographical distribution. Tung is native to the Indo-Malaysia region and was introduced throughout the Pacific islands in ancient times (KRISNAWATI et al., 2011). It is distributed across almost all islands in the Indonesian archipelago, with total cultivation area reported to be around 205-532 ha (DIRECTORATE OF PERENNIAL CROP CULTIVATION, 2008).

The tree has also been successfully introduced in Bahamas, Bangladesh, Barbados, Brazil, Cuba, Dominican Republic, India, Jamaica, Japan, Kenya, Netherlands Antilles, Trinidad and Tobago, Uganda, United States of America and Virgin Islands (US), among others

(ELEVITCH AND MANNER, 2006).According to Reitz (1988) and Elevitch and Manner (2006), *Aleurites fordii* is a medium-sized tree with a large spreading crown (Figure 1a) that can reach approximately 3-9 m in height. Crooked trunks and irregular, wide, spreading or pendulous side branches are typical features of this tree. The bark is grey-brown in colour, and fairly smooth with fine vertical lines. It has very distinct leaves, which are 3 to 5-nerved from the base, alternate and simple, with entire, wavy margins. The leaf blades ranged between 10–25 cm long with 2 glands at the junction of the leaf base and petiole that secrete a sweetish sap (Figure 1c). The colour of the fruit is green to brownish and is laterally compressed, ovoid to globose indehiscent drupe, 5–6 cm long by 5–7 cm wide (Figure 1c). Each fruit normally contains 3 to 7 seeds, however, 1 seed may be found. According to Reitz (1988), the tung flowers appear before the leaves, after the winter dormancy period, with white petals and purple streaks, comprising eight to ten stamens (Figure 1b).

Ecologically, tung is known for its ability to grow well on slopes, even steep gullies where mechanization is impossible, as found in mountain regions of Rio Grande do Sul state of Brazil. In addition, it is adaptable to this region because of the cold weather required to achieve good productivity (BIODIESEL NOTÍCIAS, 2008).

Aleurites fordii can grow on a variety of soils, including loams, clay ground, sand and limestone. The tree requires free drainage, lightly acidic to alkaline soils with a pH ranging from 5–8. It is quite drought tolerant and can grow well on relatively poor sites when well established with enough soil moisture, particularly during establishment It prefers full sun and can grow as a pioneer species in open fields with suitable rainfall (ELEVITCH AND MANNER, 2006).

The traditional uses of tung are extensive. In Indonesia, it has long been grown for subsistence and commercial purposes, sustaining people's everyday lives, especially in the eastern part of the country. It finds application in medicine, cosmetics industry and in cuisines. Tung oil is irritant and laxative and used just like castor oil. The remaining seed cake after oil removal is used as fertilizer. Similarly, tung trees are used as wind brakes and borders, shade, soil stabilization and improved fallow (KRISNAWATI et al., 2011). In Brazil, few people have heard of the tung oil crop. Tung was introduced over 40 years ago and is produced mainly in the mountain region of Rio Grande do Sul state, where mechanized farming is impossible. About a decade ago, many producers have virtually abandoned tung production because, besides experiencing low patronage, prices do not compensate. However, interest increased because the seed, which contains an oil used in the chemical industry, is also harnessed to make biodiesel and with the increased demand for biodiesel, this scenario

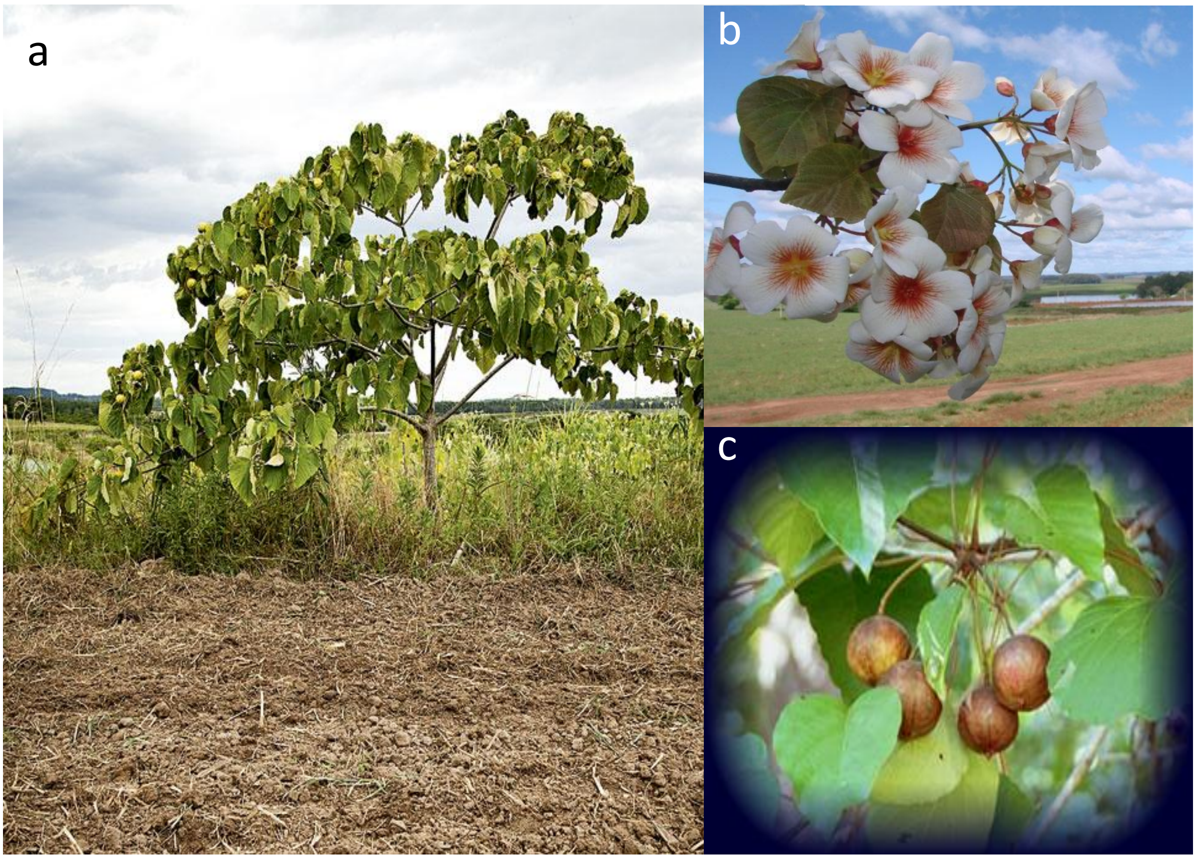

Figure 1. (a) A 4 year old Tung (*Aleurites fordii*), (b) inflorescence and (c) wavy leaves and fruits of Tung. *Source: www.retendomomentos.blogspot.com*

has changed. According to a survey conducted in Rio Grande do Sul state, the area grown to tung is around 365.37 hectares, with an average yield of 3,719 kg offruit per hectare, compared with United States of America where the productivity ranged from 4,500 to 5,000 kg of fruit per hectare (BIODIESEL NOTÍCIAS, 2008).

Despite its wide distribution and easy to grow, tung has not been planted in large-scale plantations as it is extensively cultivated in home gardens, and in and around farms and in wide inter- and intra-row spacing, such as 2x2 and 3x3 m for wind brakes (ELEVITCH AND MANNER, 2006); 4x4 m for pure stands (DALI and GINTINGS, 1993); 8x8 and 10x10 m for oil production (DIRECTORATE OF PERENNIAL CROP CULTIVATION, 2008). In tung oil production, the wide spacing can promote soil degradation, especially when young and the soil is virtually bare, hence there is the need to protect the soil, especially the surface layer. Similarly, it takes about five years for the tung tree to be established and begin full production, giving room to cultivate early maturing crop species as intercrops between the tung rows (MURANINI et al., 2009). Therefore, annual and early-maturing oilseed crops such as maize, soybean, crambe (*Crambe abyssinica*), sunflower (*Helianthus annuus*) and peanut (*Arachis hypogaea L.*) can be used in the agroforestry system, geared towards intensive feedstock production for biodiesel (JASPER et al., 2010; ROSCOE and DELMONTES, 2009).

2.2 Effect of tillage on soil properties

Soil tillage is one of the basic and important components of agricultural production technology, with a wide range of tillage equipment, practices and systems have been employed by farmers, providing opportunities to good tilth for root proliferation, incorporate crop residues and amendments into the soil, increase infiltration, increase effective root volume of shallow soil and enhance environmental performance (PRIHAR; LAL, 1990). These opportunities have made soil tillage a popular focus of environmental policies and programs such as environmental indicators for agriculture (LOBB et al., 2007).

Soil tillage produces a suitable tilth for crop growth by temporarily decreasing bulk density and increasing the volume of macropores (LOGSON et al., 1990), modifies soil thermal regime (ANDRADE et al., 2010), however, the adoption of heavy and sophisticated machinery tillage has resulted into detrimental effect on soil properties such as surface heating, water loss by evaporation, loss of pore continuity and tortuosity, compaction, increase in bulk density and loss of organic matter loss; environment (soil crust and erosion) and reduced yield (Al-KAISI and YIN, 2005; FRANZLUEBBERS, 2002; SILVA et al., 2006; REICHERT et al., 2007, 2009a; RUSU et al., 2009). Therefore, conservation tillage systems termed reduced, minimum or no-tillage are now advocated to improve degraded soil structure, control erosion and return organic matter loss occasioned by conventional tillage.

Despite the advantages of the different systems, the success is site, crop and time specific. In this context, several authors have studied the influence of different tillage techniques on soil physico-hydric properties across locations, soil types and experimental designs but results are not the same. In a study in United State of America, Liebig et al. (2004) found that continuous crop, NT system had significantly more soil organic carbon, particulate organic matter, greater aggregate stability as well as faster infiltration rates (55.6

cm hr^{-1}) relative to CT system. They affirmed that continuous crop NT system was improved with respect to its ability to provide a source for plant nutrients, withstand erosion, and facilitate water transfer.

In a long term study by Viega (2005) on soil properties after nine years of soil management systems and effect on corn production in southern Brazil, NT showed greater BD and lower Pt and Ma than other treatments. All tillage systems gave higher compaction degree at depth of about 15 cm. The superficial layer of NT had higher soil strength as determined by pre-compression stress and penetration resistance. Higher soil temperature and daily amplitude were recorded in tilled plots. After rainfall, soil moisture reduced faster in Chi, followed by CT, however higher soil moisture and lower water tension were obtained in NT even during long period of hydric deficits, resulting in higher water storage and availability to corn. The author concluded that higher water availability seems to be a major factor in determining higher crop growth and yield in NT treatments.

He et al. (2009) working on soil physical properties and infiltration rates after long-term no-tillage and ploughing in China found that NT significantly reduced BD (7.1%) in the 20-30 cm soil depth compared with CT systems, increased Ma (17%) and saturated hydraulic conductivity (249%) in the 15-30 cm soil layer but no significant difference between the treatments in the 0-15 cm depth. Moreover, plant available water and infiltration rate was greater in the NT treatments. They concluded that the improved soil quality indicators show that NT with residue retention is a promising soil management for dryland farming in China.

In Brazil, Kaiser (2010) working on soil structure and water availability in an Alfisol under different tillage in corn crop reported that compacted no-tillage (NTC) increased bulk density (BD) and reduced total porosity (Pt) and macropores (Ma) in the soil profile whereas chiseling (Chi), sub-soiling (Sub) and conventional tillage (CT) reduced BD and increased porosity while saturated hydraulic and air conductivity were less affected by the tillage treatments. No-tillage (NT) did not store more water for plants in relation to CT, Sub and Chi treatments. Soil compaction increased the water retention in densiest layer, but reduced the plant's ability to exploit the soil, by inhibiting root growth and reduce soil aeration Fontanela (2012) in her studies on physical management of an Alfisol for the establishment of sugarcane and cassava for ethanol production in southern Brazil reported that CT and Chi altered an already compacted no-till layer by reducing the BD and increasing the Pt and macropores. However the compacted NT modified the soil as the BD was increased and soil pores was altered, as well as reduction in Pt and macropores resulting in low water and air conductivity. The results also showed that NTC and Chi retained more water in sugarcane while NT and

Chi had more water in cassava. Dalmago et al. (2009) working on retention and availability of water to plants in soils under no-tillage and conventional tillage in Brazil reported that no-tillage increases the water availability to plants and reduces the energy of retention in the upper soil layers compared with conventional tillage system. The differences in soil bulk density and pore dynamics of soils under CT and NT systems affect water retention (BESCANSA et al., 2006), principally by capillary effect. Capillarity in linked to the affinity of soil particles to water, depending on pore geometry (form, size, orientation and distribution) which is strongly affected by management practices (RASIAH and AYLMORE, 1998). Soil disturbance increases the amount of pores, but disconnects them (LAMANDE et al. 2003), which jeopardizes their efficiency to the flow of water and air. Moreover, tillage-induced compaction destroys macropores (ALAOUIand GOETZ, 2008), sorptivity and reduces the water in the soil aggregates (LIPIEC et al., 2009), which also interferes with the availability of water to plants. Adsorption is another phenomenon influencing water retention, strongly related to soil texture (HILLEL, 1998) but not affected by management practices.

Martinez et al. (2008) did not find significant effect of tillage on BD and wheat yield in Chile. However, penetration resistance was higher in NT compared with CT. In contrast, drainable macropores, particle density and infiltration were higher in CT than NT plots. They concluded that long-term NT enhanced aggregate stability but other soil physical parameters were negatively influenced.

2.3 Crop residue mulching and soil properties

Arable farming with the retention of crop residues is a management system whereby at the time of crop emergence, at least 30% of the soil surface is covered by organic residue of the previous crop. The use of crop residue mulch has become prominent in the USA, where more than 35% of the cropped land is under residue mulch since the mid-1990s (CTIC, 2000).

Crop residue mulching has profound implications for crop management. It implies a set of necessary practices that ensure the retention of sufficient residues as mulch including complementary adaptations to be able to grow a crop and/or maintain productivity levels (ERENSTEIN, 2002). On the other hand, systems involving crop residue removal and burning from crop fields could constitutes potential for loss of nutrients and organic matter from the soil system and, in turn, deteriorates the physical quality of the soil (MAHMOOD-

UL-HASSAN et al., 2013). According to Singh et al. (2005), crop-residue removal or burning causes not only a decline in soil quality but also increase air pollution. Therefore crop residue recycling constitutes an important management practice aimed at restoring lost soil organic matter (SOM). Soil organic matter accumulation through residue retention or incorporation improves soil structure and resilience of infiltration and water-holding capacity, reduces soil temperature extremes and evaporation, which are impetus for sustainable crop production (BLANCO-CANQUI and LAL, 2011). However, the amount of SOM accumulation is dependent on the annual addition of organic materials, the C/N ratio whether grass or legume residue; rate of decomposition which depends on climatic conditions (DE RIDDER and VAN KEULEN, 1990).

Mahmood-ul-Hassan et al. (2013) working on physical and hydraulic properties of aridisols as affected by nutrient and crop-residue management in a cotton-wheat system in Pakistan reported significantly increased in soil organic matter (SOM) content in both the soils was with nutrient-management treatments applied in combination with crop-residue recycling. They found increase in SOM content, which in turn, decreased soil bulk density, improved macro- and meso-porosity, and enhanced percent recovery of stable aggregates. The authors opined that the result of aggregation depends on crop residue incorporation rather than clay content of the soils. However, this is contrary to the findings of Wagner et al. (2007) who suggested that macro-aggregation largely depends on soil clay content rather than straw incorporation. However, the increased macro- and meso-pores volumes (inter-aggregated pores) enhanced water storage capacity in the soil profile; by increasing infiltration, and water retention due to increased SOM. The unsaturated hydraulic conductivity was higher in treatments where crop residues were incorporated than plots with crop residues removal at given water content.

Long time studies on sugarcane management in South Africa suggests that residue burning before harvesting resulted in decreased soil organic matter (DOMINY, 2002). Similar declines in carbon fractions were observed by Blair (2000) in Australian sugarcane field as a result of residue burning. Ball-Coelho et al. (1993) working on pre- and post-harvest burning of the first sugarcane ratoon crop in Brazil reported that 2600 kg C ha^{-1} and 17 kg N ha^{-1}; 4800 kg C ha^{-1} and 42 kg N ha^{-1} were lost by convection for the two treatments, respectively. On the contrary, residue mulching gave marginal improvements in shoot population and cane yield over no mulching (RANA et al, 2003) while Graham et al.(2002) found that residue retention after harvest increases readily decomposable organic matter content in the top 10 cm soil depth, which can contribute to less fertilizer inputs. Soil nutrients loss such as the important ones described above shows how the soil condition can change over time due to residue burning or removal management and therefore can affect soil aggregation, porosity, water availability and crop production potential. Therefore, crop residue management is not just a simple add-on technology, but instead a complete package of cultural practices, the actual potential depending on the comprehensive assessment of the socio-economic implications of the implied changes. However, this potential is site-specific (ERENSTEIN, 2002).

2.4 Effect of tillage and residue mulching on soil temperature

Soil temperature plays a significant role in land superficial processes, especially in energy balance applications such as modeling of land surfaces, numerical weather forecasting and climate prediction (HOLMES et al., 2008). It is an important soil property of great important during crop germination and early development (BLANCO-CANQUI and LAl, 2011). Soil temperature controls the rate of evaporation and aeration, the modes and rates of chemical reactions, nutrient availability and cycling as well as biological and microbial activities occurring in the soil (van DONK et al., 2004).

The effect of tillage and residue mulching on soil thermal regime has been a subject of research. Odjugo (2008) reported that soil temperature at the 0-10 cm was significantly higher in conventional tillage than under no-tillage and the mulched treatment had significantly lower soil temperature than no mulch. Working on the effects of soil tillage and mulching on thermal performance of a Luvisol topsoil layer Andrade et al. (2010) found significantly lower soil temperature in the profiles covered by straw mulch. In a similar study by Eruola et al. (2012) in a tropical climate, grass mulch significantly lowered maximum soil temperature by 1-2 ^{o}C at 15 cm depth during the extreme thermal time. Similar soil temperature response to mulching was reported by Agele et al. (2010).

2.5 Soil tillage and residue mulching effects on crop yield

Crop productivity integrates all the complex and dynamic soil properties and processes. Soil properties and processes are often perturbed by the medication caused by management practices, thus influencing crop growth and yield. The effects of soil microclimatic modification by tillage and residue management on crop yield have been studied (AGBEDE, 2006; ODJUGO, 2008; FONTANELA, 2012; MOHAMMAD et al., 2012), however, results are contradictory. Tillage influences crop growth and yield by altering soil structure, pore space and moisture removal pattern over the growing season. Unfortunately, there has been no well-defined relationship between soil tillage and crop yields due to diverse soil types, regional climate and crop physiology.

Fontanela (2012) working on establishing sugarcane crop using different tillage methods found highest sugarcane yield in no-tillage compared with conventional and other tillage methods. The author attributed the increased yield to better soil conditions provided by no-tillage. The reduction in crop yields in compacted tillage was linked to the availability of water to plants, however, Cardoso et al. (2006) and Reichert et al. (2009a) affirmed that compacted layers do not affect production when there is enough water during the crop cycle.

In contrast, Agbede (2006) and Odjugo (2008) reported higher crop yield in conventional tillage than traditional no-tillage system. Mohammad et al. (2012) working on the effect of tillage, rotation and crop residues on wheat crop productivity, fertilizer nitrogen and water use efficiency and soil organic carbon status in rainfed region of north-west Pakistan, reported that wheat grain and straw yield was not increased by tillage treatment.

Residue mulching promotes crop productivity by strengthening nutrient cycling and replenishing soil nutrients, enhances aggregation through increased soil organic matter concentration, conserves soil water by reducing excessive evaporation and promotes biological activity (WILHELM et al., 2007). Studies conducted in various sugarcane areas of the world has shown that crop residue retention on the soil surface following harvesting have considerable yield responses in low rainfall regions (KINGSTON et al., 2005). Ball-Coelho et al. (1993) found greater cane yield in the first ratoon crop in the mulch plot than the burn treatment, 54 and 37 Mg ha^{-1}, respectively. The authors observed that the yield response is attributed to increased soil water retention and reduced weed growth under the residue mulch. They concluded that despite the short-term trial, crop residue retention proved to be an alternative to the traditional burn system. Rana et al. (2003) in a study on the effect of trash mulching and N fertilizer on growth and yield of sugarcane in India found marginal improvement in shoot population, shoot height, dry matter and cane yield in mulched plots over no mulching. They observed that individual cane weight showed significant increase with trash mulching, 767 g, compared with no mulch, 740 g in the first year and an increase from 724 to 751 g in the second year of evaluation. They concluded that the improved yield attributes resulted in 3.2 and 5.8 % increase during the 2 seasons.

2.6 Agroforestry practices and soil properties

Agroforestry systems share many processes, such as environmental change, competition for resource use and nutrient transfer. Ong et al. (1996) reported that belowground competition is an important phenomenon in alley cropping systems and research has focused on efficient use of resources, such as water and nutrients and the effects on soil structural condition.

Livesley et al. (2004) in their study on competition in tree row agroforestry systems, soil water distribution and dynamics in western Kenya found greater amount of water was stored under the maize monocrop than the intercropping systems. In the grevillea-maize system, stored soil water increased with increasing distance from the tree row but in the senna-maize system, there was a decreased between 75 and 300 cm from the hedgerow. Soil water content at the end of the cropping season was similar to that at the beginning of the season in the grevillea-maize system, but about 50 and 80 mm greater in the senna-maize and sole maize plots, respectively. The possible benefits of reduced soil evaporation and crop transpiration close to a tree row were not evident in the grevillea-maize system, but appeared to greatly compensate for water uptake losses in the senna-maize system.

Despite the competition for resource use, several studies have hypothesized agroforestry systems to improve soil physical and hydraulic properties (SEOBI et al., 2005; AGUIAR, 2008). Fan et al. (2006) investigating the effects of intercropping systems of trees with soybean on soil physic-chemical properties in juvenile plantations in China found that soybean intercropping with larch and ash improved soil physical properties after one growing season. The soil bulk density in larch/soybean and ash/soybean systems was 1.112 and 1.058 g cm^{-3}, respectively, lower than that obtained in the sole larch or ash plantation. Similarly, total soil porosity increased after intercropping while the organic matter content in the larch/soybean and ash/soybean intercrops was 1.77 and 1.09 times higher than that observed in the sole larch and ash plantations, respectively. The authors concluded that soil physical properties were improved after intercropping trees with soybean and they advocated further studies to investigate the long-term effects of intercropping with soybean on woody tree species.

In a study by Anderson et al. (2009) on soil water content and infiltration in agroforestry buffer strips in United States, no significant difference in quasi-steady infiltration rates was found among the treatments. However, agroforestry had significant lower soil water content than row crop areas during the growing season. Higher water content obtained after the principal recharge event in the agroforestry treatment was attributed to better infiltration through the root system. The results show that agroforestry buffer strips could reduce soil water content during critical times such as fallow periods, as well as increase water infiltration and water storage and could be strategy to reduce surface runoff and soil loss from watersheds.

In another study by Seobi et al. (2005) on the influence of grass and agroforestry system on soil hydraulic properties of an Albaqualf, significant lower soil bulk density ($p < 0.05$) by 2.3% was obtained in the grass and agroforestry buffers compared with the row crop areas. Total porosity and coarse mesoporosity (soil pore, 60- to 1000-μm diameter) were 3 and 33% higher ($P < 0.05$), respectively, for the grass and agroforestry treatments than the row crop treatment. The saturated hydraulic conductivity was three and 14 times higher ($p < 0.05$) in the grass and agroforestry buffer treatments compared with the row crop treatment. Similarly, the potential water storage in the grass and agroforestry buffer treatments increased by 0.90 and 1.1 cm, respectively, per 30-cm depth compared with the row crop treatment, indicating agroforestry buffers could be beneficial by reducing surface runoff from row crop management.

2.7 Soil quality

Because of the multiple functions that the soil resources must provide and in response to increased global emphasis on sustainable land use and with a holistic focus that sustainable soil management requires more than soil erosion control, the discussion on soil quality intensified in the early 1990s (KARLEN et al., 2003). However, the development of soil quality concept was first advocated by Warkentin and Fletcher (1977). Following this, soil quality was not discussed in literature for nearly a decade because the primary emphasis of soil management was on controlling erosion and minimizing the effect of soil loss on productivity (PIERCE et al., 1984). In the mid-1980s, the Canadian Senate Standing Committee on Agriculture prepared a report on soil quality and revived the concept (GREGORICH, 1996). Shortly after, Larson and Pierce (1991) defined soil quality as the capacity of a soil to function within the ecosystem boundaries and to interact with surrounding ecosystems.

Continuing this thought, Doran and Parkin (1994) proposed the following concept to soil quality, which was later reworked by Doran (1997) and is still utilized today: "Soil quality is the capacity of a soil to function within the limits of natural and managed ecosystems, to sustain plant and animal productivity, maintain or enhance the quality of air and water and to promote the health of plants, animals and men." In other words, it is the ability of the soil exert it functions in nature (DORAN, 1997), which include medium for plant growth; compartmentalize and regulate the flow of water in the environment; stock and promote elements cycling in the biosphere; and serve as a buffer in the formation, degradation and mitigation of adverse compounds in the environmental (LARSON and PIERCE, 1994; KARLEN et al., 1997). This capacity or ability results as a result of interactions between innumerous physical, chemical and biological processes of complex nature (TÓTOLA and CHAER, 2002).

2.7.1 Soil quality indicators

Soil quality has never been measured directly, but is inferred from measuring changes in its attributes or attributes of the ecosystem, referred to as indicators. These indicators may be directly monitor in the soil, or monitor the outcomes that are affected by the soil, such as biomass, improved water use efficiency, aeration, and sustainability of soil management systems (SHUKLA et al., 2006). The indicators which directly monitor soil quality are grouped as visual, physical, chemical, and biological indicators. In other words, soil quality is the integration of biological, physical and chemical properties of the soil that enables it to perform its intended functions. Nortcliff (2002) affirmed that there are numerous potential soil properties which can serve as soil quality indicators, and research is required to identify the most suitable. In this context, a wide range of soil quality indicators have been identified (KARLEN et al., 1992; PARR et al., 1992; CHAUDHURY et al., 2005; MAIRURA et al., 2007), however, the indicators used or selected by different researchers in different regions are not the same because of inherent regional soil properties and purpose of assessment (SHUKLA et al., 2006). Mandal et al. (2013) reported that soil quality can be influenced by many properties inherent to a particular soil and reflective of the environmental factors affecting long-term soil formation. They stressed further that soil quality could follow the condition of the soil emanating from the alteration of certain soil properties and processes by management. Therefore, it has not been possible to develop a single list of indicators which can be universally suitable for all purposes. However, for the selection of indicators be of great value, investigators should ensure that they: (i) correlate well with natural processes within the ecosystem, (ii) integrate tangible soil physical, chemical and biological properties and processes, and serve as basic inputs required for predicting properties or functions that are more difficult to measure, (iii) be relatively easy to use under field conditions and be applied in different scenarios, (iv) be sensitive to variation in management and climate, and (v) be components of exiting soil databases where possible (DORAN et al., 1996, CHEN, 1998).

2.7.2 Indexing soil quality indicators

Soil structural quality status is result of combined physical, chemical and biological processes as a reaction to management practices (ISLAM, 2006). However, interpreting soil quality status by mere monitoring changes in selected indicators cannot give the desired information about soil quality (SHARMA et al., 2008). According to these authors, the recent approach is the normalization of the data from measurements and conversion to a more robust numeric value, called “soil quality index”, than mere static descriptor. Therefore, combining the indicators to a single index has been more precise to gauge the level of aggrading, sustaining or degrading soil condition (BUCHER, 2002; WIENHOLD et al., 2004). MASTO et al. (2007) opined that the concept of soil quality index is a tool to help quantify the combined physical, chemical and biological response of soil to soil and crop management practices.

Indexing soil quality involves three major steps. The first step entails defining system’s management goals (for example, water entry, retention and release; nutrient cycling; plant growth and development, yield) (Figure 2). After this, selection of appropriate soil quality indicators that can be efficiently and effectively used to monitor critical soil functions as determined by the specific management goals for which the evaluation is being performed follow (Figure 2) (ANDREWS et al., 2002a; KARLEN et al., 2003).The selected indicators collectively formed what is known as the “minimum data set (MDS)”. The selection of MDS has been achieved using expert opinion (EO) technique or simplified by statistical methods (ANDREWS et al., 2002b).

The EO technique is used to select MDS according to consensus of researchers, experience, recommendations in the literature (DORAN and PARKING, 1994)and common management concerns (ANDREWS et al., 2002a). On the other hand, statistical approach includes principal component analysis (PCA), multiple correlation, factor and cluster analysis and star plots. The PCA is the major statistical step to select MDS, the principal components (PCs)

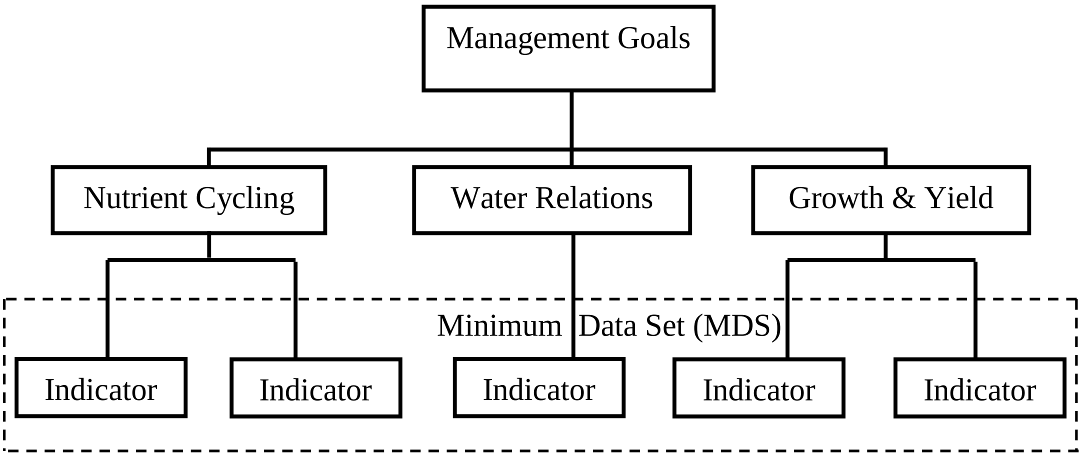

Figure 2. A framework for selection of indicators for the minimum data set (MDS).
Adapted from: Karlen et al. (2001) and Andrews et al. (2002a).

(PCs) for a data set being defined as linear combinations of the variables that account for the highest variance within the set by describing vectors of closest fit to the *n* observations in *p*-dimensional space, subject to being orthogonal to one another (DUNTEMAN, 1989). Andrews et al. (2002a) working on a comparison of soil quality indexing methods for vegetable production systems in northern California reported that there is no significant difference between the EO and PCA selection techniques.

Each of the selected indicators is then transformed by scoring, using ranges established by the soil’s inherent capability to set the boundaries and shape of the scoring functions (Figure 3). The essence of this step is to ensure that the observed physical, chemical and biological

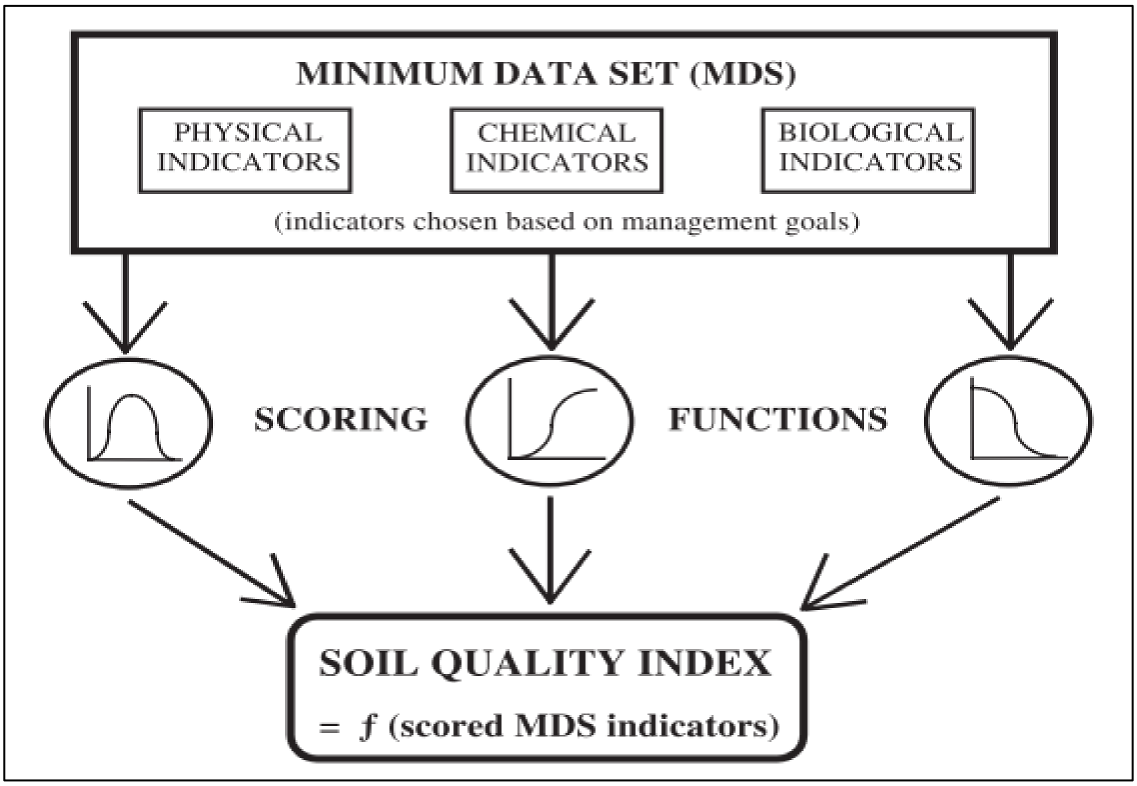

Figure 3. A conceptual model for integrating minimum data set indicators to index values. A*dapted from: Karlen et al., 200*3.

indicators with different units can be combined (e.g., soil BD (g/cm^3); earthworm count (no unit); total nitrogen (g/kg) pH (no unit). Scoring of indicator has been accomplished in a variety of ways, namely: linear or non-linear, optimum, more is better, less is better, more is worse etc, depending upon the intended soil function. It is interesting to note that for some management goals, some indicators can be used for different functions or scored in different ways (KARLEN et al., 2003).

The last stage is the integration of transformed indicators into an overall index of soil quality, which can be achieved using additive, weighted additive or hierarchical decision support indexing methods (Figure 3) (ANDREWS et al., 2002a). The overall index is then used to evaluate the effects of different practices on similar soils or temporal trends on the same soil.

2.7.3 Management practices and soil quality

Soil and crop management practices such as tillage, multiple cropping and crop rotation systems, residue management and increased input of carbon affect soil quality (SQ) in different ways (YAO et al., 2013). According to Xu et al. (2006), SQ indicators are sensitive to change in land use, management or conservation practices. A difference in management practices often results in differences in soil physical, chemical and biological properties, which in turn results into changes in functional quality of the soil (ISLAM and WEIL, 2000). In this context, several studies have been conducted worldwide to evaluate how SQ indicators respond to various treatments or land management scenarios (AZIZ et al., 2011; GILLEY et al., 1997; IMAZ et al., 2010; JACKSON et al., 2003; LEE et al., 2006; LI et al., 2004; SHARMA et al., 2008; XU et al., 2006; YAO et al., 2013), but response differed and identified significant indicators are not the same, mainly as a result of regional nature of soil quality. Imaz et al. (2010) working on soil quality indicator response to tillage and residue management in semi-arid Mediterranean cropland reported that resistance to penetration, particulate organic matter (POM), aggregate stability and total organic matter were significant SQ indicators, positively correlated with soil water retention and the quality index significantly higher in NT treatment. Management of soil organic matter to improve soil quality through practices such as reduced tillage and crop residue retention could improve nutrient availability for subsequent crops, and enhance surface structural conditions (KING, 1990).

In another study on the short-term effect of cultivation and crop rotation systems on soil quality indicators by Yao et al. (2013), cotton-barley rotation had higher SQ index values over rice-rape rotation (0.523 vs 0.422). They identified soil organic carbon density, available K, bulk density, groundwater table and electrical conductivity as the minimum data set for soil quality assessment as they possessed the potential in discriminating the effect of rotation systems on soil quality. Cultivation practices change soil water status, pore space and the degree of mixing of crop residues within the soil matrix, thereby affecting soil organisms, which have important functions, such as structural improvement, nutrient cycling and organic matter decomposition (SHARMA et al., 2005). However, Lee et al. (2006) did not find bulk density as an effective soil quality assessment indicator. They stated that for intensively cultivated medium-textured soils in the sub-tropical zone, bulk density may not reflect the effects of manure application on soil quality. Aziz et al. (2011) used another combination of physical, chemical and biological indicators to assess the impact of crop rotation on soil quality. They reported that crop rotation had significant impact on all the indicators except total porosity. The soil biological, chemical and physical quality were improved by 23, 16 and 7%, respectively, under corn-soybean-wheat-cowpea rotation system than sole corn. They concluded that multiple cropping systems could be more effective for maintaining and enhancing soil quality than sole cropping.

Chaudhury et al. (2005) in their studies on soil quality assessment in a rice based cropping system identified total soil N, available P, dehydrogenase activity and mean weight diameter (MWD) of aggregates as the key indicators for alluvial. Sharma et al. (2008) found key indicators towards soil quality as microbial biomass carbon, available N, DTPA-Zn, DPTA-Cu, hydraulic conductivity, and mean weight diameter. However, tillage did not influence the SQI while the combined use of tillage and compost amendment significantly increased soil quality. Increased input of carbon enhances soil aggregation, increase porosity and reduce bulk density, which are candidates of soil quality status.

From the above reports, there is no clear or standard set of soil quality indicators that could be universally adopted. Thus, the search for soil indicators to define optimum soil quality for plant growth and also as a criterion in decision making to set management strategies are still under investigation, and possibly to actualize a way more reliable, should integrate soil properties and processes, meteorological variables and crop growth stages. Therefore, site specific assessment of soil quality is necessary to reflect how well soil performs its intended functions, to determine the suitability of adopted management systems as related to agricultural production practices.

2.8 Time-series analysis

For years, different treatments in a homogeneous domain remain the major approach by which research in soil science is conducted in Brazil and elsewhere with the use of classical statistical analysis of variance or multiple regressions. These studies normally neglected the influence of spatial and temporal heterogeneity of field soils and weather conditions, respectively, in order to improve the efficiency of the classical statistics, ignoring the facts that observations are either spatially or temporally independent of each other and that mean values are based on normally distributed sets of measurements (NIELSEN and

WENDROTH, 2003). Nielsen and Alemi (1989) affirmed that observations conducted using the traditional classical statistics have yielded to results between and within treatments which are not always independent, thus weakening the statistical design and making it impossible to apply in another place or different scenario.

Based on the weakness pointed out by Nielsen and Alemi (1989), soil scientists, environmental engineers and hydrologists are now complementing field evaluations with other statistical tools and approaches such as geostatistics, neural networks and state-space (time) to examine data observed at different points or periods with a view to understanding the structure of spatial and temporal distribution of soil-plant-atmospheric processes at different scales (WENDROTH et al., 1997; HUI et al., 1998; WESTERN et al., 2002; TIMM et al., 2003a, 2003b, 2006; HU et al., 2008). According to Timm et al. (2011), research in soil science in the last few decades has focused on the study of soil spatio-temporal variability with the aim of better understanding of the processes that influence the variability of crop production. Coelho et al. (1998) asserted that the importance of spatial and temporal variability of soil chemical and physical properties and their relation to crop yield cannot be over-emphasized for sustainable soil management and crop production. Thus, the analysis of soil physical and hydraulic properties using state-time models, coupled with other statistical parameters has gained prominence in soil research (WENDROTH et al., 2001; TIMM et al., 2011).

2.8.1 Indexes of time-series analysis

Some indexes are used to analyze and interpret a time series data including: (i) autocorrelation, (ii) cross-correlation, (iii) spectral and co-spectral analysis, and (iv) coherency. However, this study will be limited to autocorrelation and cross-correlation.

The degree of linear association between pairs of values separated by a given time distance is obtained from the self- or autocorrelation coefficient. The autocorrelation function or correlogram is a plot of the autocorrelation coefficient versus time distance between pairs of measurement. The autocorrelation length is that separation distance beyond which the autocorrelation is considered nil because it is not significantly different from zero. The autocorrelation function is a primary diagnostic measure that indicates if we will be able to obtain a temporal interpretation of on-site sampled data. Once this is achieved, one is no longer limited to comparisons between treatment means but is already on the path to define a temporal process that can be interpreted with sampling other temporally correlated properties.

While each kind of measurement manifests its own temporal autocorrelation, an analysis of cross-correlation reveals over what distance in time the two kinds of measurements are related to each other. Thus, the degree of linear association between pairs of the two different kinds of values separated by a given distance is quantified by the cross-correlation coefficient (NIELSEN and WENDROTH, 2003).

2.8.2 Temporal processes of soil water storage

Among the soil properties, soil water content is the most important state variable in hydrologic and biologic processes (CHOI and JACOBS, 2007) because it is highly dynamic in space due to soil variability and in time, being influenced by soil properties and controlled by the weather and this spatio-temporal variation are key factors for understanding various hydrological processes at different scenarios.

Soil water status near the surface or in the soil profile has received attention in terms of spatio-temporal analysis (WENDROTH et al., 1999; MOHANTY and SKAGGS, 2001; MORETI et al., 2007; GAO and SHAO, 2012; SUR et al., 2013). However, data on soil water content and related properties have been observed along lines or in transects in a single campaign, forming spatial data series, and these kind of data series have been by applying statistical tools from the Time Series Analysis using the analogy between sequence of data collected over time, t, at a given location and a space series of data, x, observed at a given time, by substituting “t” for “x” (TIMM et al., 2003a, b, 2006). Although the state-space approach comes from the Time Series Analysis, it has successfully been applied to study the spatial variability of soil water content and other properties collected along spatial transects (MORKOC et al., 1985; DOURADO-NETO et al,. 1999; TIMM et al., 2004).). Despite this quantum of studies, there is limited research on temporal variability of soil water status (ABOITIZ et al., 1986; TIMM et al., 2011). Timm et al. (2011) working on temporal variability of soil water storage (*S*) on a coffee field and how it is influenced by other soil-atmospheric variables in Brazil reported that temporal stability of soil water storage was again demonstrated, in which wetter or dryer locations remain so over time, and the definition of such positions in the field reduces the number of sampling points in future *S* evaluations under similar conditions. State–time analysis shows that *S* estimations depend more on previous measurements of itself, *S*, by 71%, rainfall (*P*) by 7% and evapotranspiration (*ET*) by 18%. They also found that evapotranspiration was not realistically estimated from previous measurements of *S*; but it was more dependent on previous measurements of *ET* (59%) than on *P* (30%) and *S* (9%). They concluded that the statistical procedure showed great advantages over classical multiple regressions.

2.8.3 Temporal processes of soil temperature

Soil temperature plays a significant role in land superficial processes, especially in energy balance applications such as modeling of land surfaces, numerical weather forecasting and climate prediction (HOLMES et al., 2008). It is an important soil property of great important during crop germination and early development (CHEN et al., 2007; BLANCO-CANQUI and LAL, 2011). Soil temperature controls the rate of evaporation and aeration, the modes and rates of chemical reactions, nutrient availability and cycling as well as biological and microbial activities occurring in the soil (ZHANG et al., 2003; van DONK et al., 2004).

Soil temperature is a dynamic soil property as it changes with climatic variability and other processes. The way in which soil temperature responds to diurnal air temperature oscillations is strongly affected by soil management. In practice, soil thermal regime is usually modified by mulching application and the creation of micro-climate by tillage (ANDRADE et al., 2010). Although several studies have been carried out on the effect and soil tillage and residue management on soil temperature (ANDRADE et al., 2010; ODJUGO, 2008; ERUOLA et al., 2012), however, studies of temporal variability and covariance structure of soil temperature of crop fields under different soil management and as it is influenced by climatic factors is still incipient in Brazil or elsewhere. Morkoc et al. (1985) employed the state-space approach to estimate missing data of gravimetric soil water content using observed water content and soil surface temperatures from irrigated sorghum field and obtained high degree of correlation. Dourado-Neto et al. (1999) who first performed the state-space analysis in Brazil used the approach to describe the behaviour of soil temperature in conjunction with soil moisture in a sugarcane field under different management. They found that soil temperature was spatially dependent and related to soil water content, and that present values of soil temperature can be estimated from neighboring values, including information on soil moisture.

3 METHODOLOGY

3.1 Description of study sites.

This study was carried out at the Experimental Station and Soil Physics Laboratory of the Center for Rural Sciences, Universidade Federal de Santa Maria, Rio Grande do Sul State, southern Brazil, latitude 29° 42' S, longitude 53° 49' W, and altitude of 95 meters. The climate of the area is "Cfa" humid subtropical according to Köppen’s classification (MORENO, 1961). The mean temperature of the warmest month is above 22°C, and the temperature of the coldest month is between -3°C and 18°C. Precipitation is well distributed, with annual rainfall ranging from 1300 to 1800 mm yr^{-1}. The main soil type of the study area is Dystrophic Paleudalf, sandy loam texture (SOIL SURVEY STAFF, 2006). There were two experimental sites, one at the sugarcane field and the other, a newly established tung field, which is about 1 km from the sugarcane field.

3.2 Sugarcane Experiment

The sugarcane experiment was to investigate seasonal changes in soil quality indicators, and performance of sugarcane as a result of different tillage systems cum imposition of residue mulching as well as the adequacy of time series analysis of soil water storage and temperature.

3.2.1 Experimental design, treatments, and field management

In year 2010, the sugarcane experiment was established as a one factor (tillage) experiment in a randomized complete block design (RCBD) with three replications. The tillage factor consisted of, no-tillage (NT); no-tillage + compaction (NTC); conventional tillage (CT) and chiseling (Chi) (Figure 4).

Land preparation by the different tillage methods was made using two different tractors as shown in Figure 5. The conventional tillage (CT) was prepared by ploughing and harrowing (disc plough and harrow attached to Massey Ferguson Tractor, Model: MF 275).

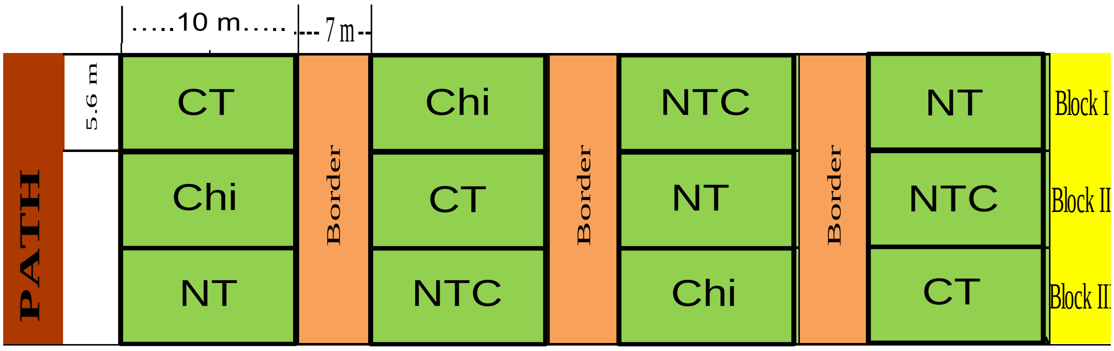

Figure 4. Layout of the sugarcane experimental field showing the different tillage methods in year 2010 at the Experimental Station of the Department of Soils, Federal University of Santa Maria, Brazil.

CT: conventional tillage; NT: no-tillage; Chi: chisel tillage; NTC: compacted no-tillage

Soil chiseling (Chi) was accomplished with the aid of a chisel plough, with three ripper shanks, spaced 0.80 m apart, with an average working depth of 0.30 m. The compacted tillage (NTC) was made by two superimposed, parallel passes of a pay loader tractor of total weight of 8 Mg. The compaction procedure was performed when the soil was at a moisture content of 0.16 kg kg^{-1}.

After the first cut in year 2011, there was no soil tillage, however, residue mulching was introduced with the splitting of each tillage plot into two equal parts (Figure 6), one part was mulched using crop residue of sugarcane harvest while the other part was left bare. The treatments became: NTM: No-tillage with residue mulching; NT: No-tillage without residue mulching; NTCM: Compacted no-tillage with residue mulching; NTC: Compacted no-tillage without residue mulching; ChiM: Chiseling tillage with residue mulching; Chi: Chiseling tillage without residue mulching; CTM: Conventional tillage with residue mulching; CT: Conventional tillage without residue mulching in three replications. Thus there were 24 plots, each 5.6 m x 5 m and a border, 7 m wide, giving a total area of about 0.10 ha. The application of residue mulching treatment was repeated in year 2012.

3.2.2 Soil sampling

Disturbed and undisturbed soil samples were collected using cores (with a volume of about 102 cm^3 for physical properties and 80 cm^3 for mechanical properties) in the middle of 0-10, 10-20, 20-40 and 40-60 cm soil layers. Soil sampling was made at initial and every year (at harvest). Samples were kept in sealed plastic cases and transported to the laboratory for analysis. Where necessary, samples were kept in the refrigerator to minimize moisture lost.

Figure 5. Details of land preparation by the different tillage methods: (A) conventional tillage (CT); plough (left) and harrow (right); (B) Chisel tillage (Chi); and (C) Compacted no-tillage (NTC).

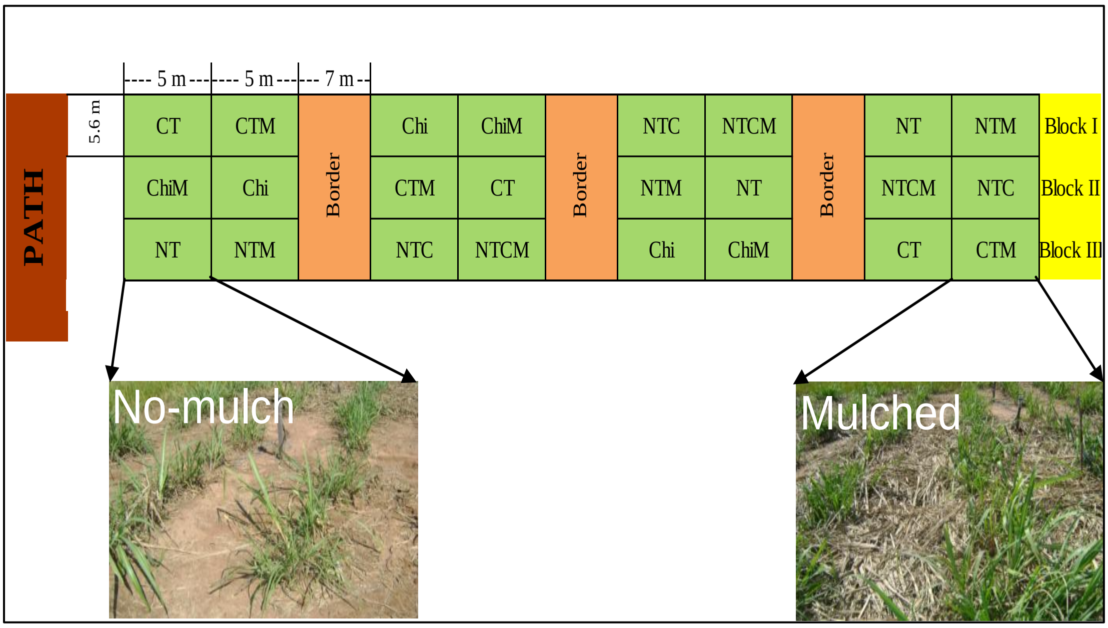

Figure 6. Layout of the sugarcane experimental field showing the different tillage methods after the introduction of sub-treatment, with and without residue mulching at the Experimental Station of the Department of Soils, Federal University of Santa Maria, Brazil.

NTM: No-tillage with residue mulching; NT: No-tillage without residue mulching; NTCM: Compacted no-tillage with residue mulching; NTC: Compacted no-tillage without residue mulching; ChiM: Chiseling tillage with residue mulching; Chi: Chiseling tillage without residue mulching; CTM: Conventional tillage with residue mulching; CT: Conventional tillage without residue mulching in three replications

3.2.3 Soil texture and chemical properties of the sugarcane field

The initial soil textural and chemical properties analyses of the sugarcane field have been done by Fontalena (2012) before imposing tillage treatments in 2010 (Table 1). The average sand, silt and clay contents as well as the texture of the soil layers of the experimental field are presented in Figure 7. The soil texture of the sugarcane field is mainly sandy loam, with very high sand content (up to 69%) in the 0-10 cm superficial layer and very low clay content (not more than 12%) even in the 40-60 cm subsurface layer (Figure 7).

According to the soil classification done by Kaiser (2010), the site has horizon E from 50 cm and horizon Bt textural from 90 cm.

Table 1. Some soil chemical properties of the sugarcane field, Department of Soils Experimental Station, Santa Maria, Brazil.

Soil layer, cm	**pH H_2O**	**P**	**K**	**Ca**	**Mg**	**Al**	**H+Al**	**ECEC**	**CEC $pH_{7.0}$**	**Sum of base**	**Saturation**	
		---mg dm^{-3}---		---------------------**Cmol$_c$ dm^{-3}**----------------							**Al**	**Base**
0-10	5.1	20	52	1.8	0.5	0.4	3.5	2.84	5.94	2.44	14	41
10-20	5.0	23	68	1.3	0.4	0.6	3.5	2.48	5.38	1.88	24	35
20-40	4.9	21	68	1.1	0.3	0.8	3.9	2.38	5.48	1.58	334	29
40-60	4.8	24	68	1.0	0.3	0.8	3.9	2.28	5.38	1.48	35	28

pH: level of acidity or alkalinity; P: phosphorus; K: potassium; Ca: calcium; Al: Aluminum; H+AL: acidity; ECEC: Effective cation exchange capacity; $CEC_{pH7.0}$: buffered cation exchanged capacity; Al: aluminum.

3.2.4 Evaluations

3.2.4.1 Laboratory analysis

1. Field capacity, permanent wilting point and maximum available water

Undisturbed soil samples collected from the soil layers for both crops were used to evaluate soil water retention characteristics. After preparation in the laboratory, the samples were equilibrated at: 0 kPa (saturation) in a water bath for 48 hours; -10 kPa water tension in a tension table (REINERT and REICHERT, 2006); and -1500 kPa water tension, using the dew point potentiometer (WP4, Decagon Equipment Inc. USA) (KLEIN et al., 2006), on disturbed soil samples, after air-dried and passed through 2-mm sieve.

The soil volumetric water content at -10 kPa water tension corresponds to the field capacity (FC), the volumetric moisture content at -1500 kPa is the permanent wilting point while the maximum available water for root extraction was computed as:

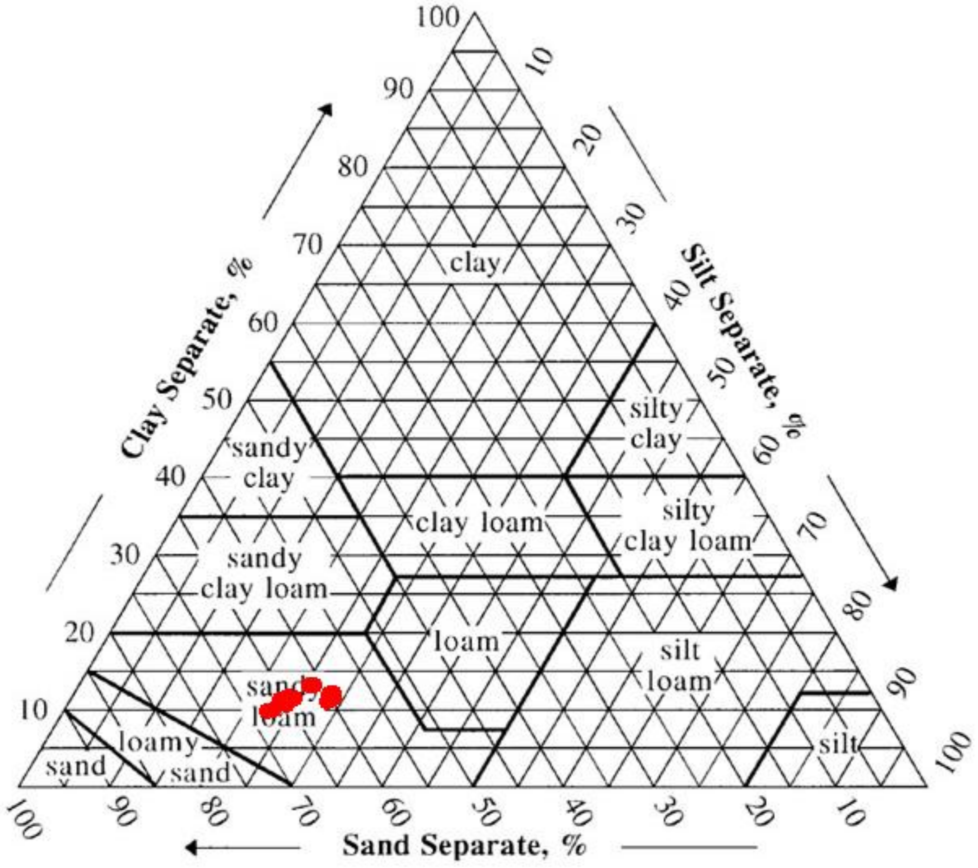

Figure 7. The average sand, silt and clay contents as well as the texture of the (a) 0-10, 10-20, 20-40 and 40-60 cm soil layers of the sugarcane field and (b) 0-10, 10-20, 20-40, 40-60 and 60-80 cm soil layers of the tung field at Santa Maria, southern Brazil.

The red circles indicate the texture.

$$AWmax = (FC - PWP) * d \text{……………..……………....…..} 1$$

where $AWmax$ is the available water content, mm; FC is the volumetric water content at field capacity (-10 kPa tension); PWP is the volumetric moisture content at permanent wilting point (-1500 kPa tension); and d is the soil thickness, mm.

2. Total porosity, macroporosity and microporosity

The total porosity (Pt) corresponds to the volumetric water content at water saturation; microporosity (Mi) is the volumetric water content at -6 kPa water tension while macroporosity (Ma) is the difference between the total porosity and microporosity (EMBRAPA,2011),

$$Ma = Pt - Mi \text{……………………………..………....................} 2$$

3. Soil bulk density

After evaluation of the soil moisture retention at 100 kPa, the soil cores were oven-dried at 105°C for 48 hours to determine the bulk density (BD), the ratio of the mass of dry soil and volume of the cylinder (BLAKE and HARTGE, 1986).

4. Soil organic matter, total nitrogen, C/N ratio and carbon pool

Soil organic carbon (SOC) and total nitrogen (TN) were quantified from the 0-10, 10-20 and 20-40 cm soil layers using auto-analyzer (Model: Flash EA 1112, Thermo Finnigan, Milan, Italy) dry combustion method (NELSON and SOMMER, 1996).

(a) Soil organic matter (SOM)

Soil organic matter was computed using the van Bemmelen conversion coefficient as:

$$SOM = 1.724 * SOC \text{………………………….……….....…......} 3$$

(b) Soil organic carbon pool (OC-pool)

The OC-pool (Mg ha^{-1}) was computed from SOC content (g kg^{-1}) for each soil layer using the equation:

$$OC - pool = SOC * BD * A * D * 10^{-3} \qquad \text{..........................4}$$

whereSOC is the soil organic carbon content (g kg^{-1}), BD is the soil bulk density (kg m^{-3}), A is the land area in ha (ha = 10^4 m^2), D is the soil depth (m).

(c) The C/N ratio

The C/N ratio was calculated as:

$$C/N = \frac{SOC}{TN} \qquad \text{...5}$$

whereSOC is the soil organic carbon content, g kg^{-1}; TN is the total nitrogen concentration, g kg^{-1}.

5. Degree of compaction.

The degree of compaction, DC, was estimated according to the equation:

$$DC = \frac{BD}{BD_{LLWR}} * 100 \qquad \text{...6}$$

where: DC: degree of compactness (%); BD: bulk density (m^3 m^{-3}); BD_{LLWR}: BD when the least limiting water range is zero (i.e. LLWR = 0) and for this soil type, BD_{LLWR} = -0.00078 x % clay + 1.83803 (Reichert et al., 2009a).

6. Soil mechanical properties

Undisturbed soil samples were collected at harvest of each growing season from 0-10, 10-20 and 20-30 cm soil layers using soil cores, about 57 mm diameter and 30 mm high. After laboratory preparation, the samples were saturated in a water bath for 48 hours and equilibrated to 10 kPa water tension (field capacity) in the tension table. The uniaxial compression test was applied on each sample using sequential loads 12.5, 25, 50, 100, 200, 400, 800 and 1600 kPa in an Oedometer device (Model: S-450 Terraload, Durham Geo-Enterprise) for 5 minutes during which 90% of the soil sample was considered to have been deformed, following the recommendation of the Brazilian Association of Technical Norms, code NBR-12007/90 (ABNT, 1990) Dias Junior and Pierce (1996). After the test, the samples were oven-dried at 105 ^{o}C for 48 hours. The pre-compression stress (σ_c) and compression index, *Ic* were computed using the Casagrande (1936) algorithm in SAS software.

3.2.4.2 Field measurements

1. Soil moisture content monitoring

In the sugarcane field, five (5) TDR sensors were installed at soil depths 0-5, 5-10, 10-20, 20-40 and 40-60 cm in each of the four (4) tillage treatments in 2010, giving a total of sixty (60) TDR sensors. However, another set of sixty (60) TDR sensors were installed in the same soil layers of mulched plots after splitting each tillage plot into two in 2011. Soil moisture monitoring during the growth cycle was read manually at different time intervals, ranging from daily, 2, 5 days; 1 or 2 weeks by connecting the soil moisture sensors to a time domain reflectometry (TDR) datalogger (TDR 100, Campbell Equip. Inc., USA). The TDR sensors have been calibrated for this soil (KAISER et al., 2010), hence the volumetric water content were measured directly, however, the calibration equation was tested periodically, when the soil was relatively wet and dry using gravimetric technique. After each reading, the soil moisture content data was downloaded via a computer (Figure 8).

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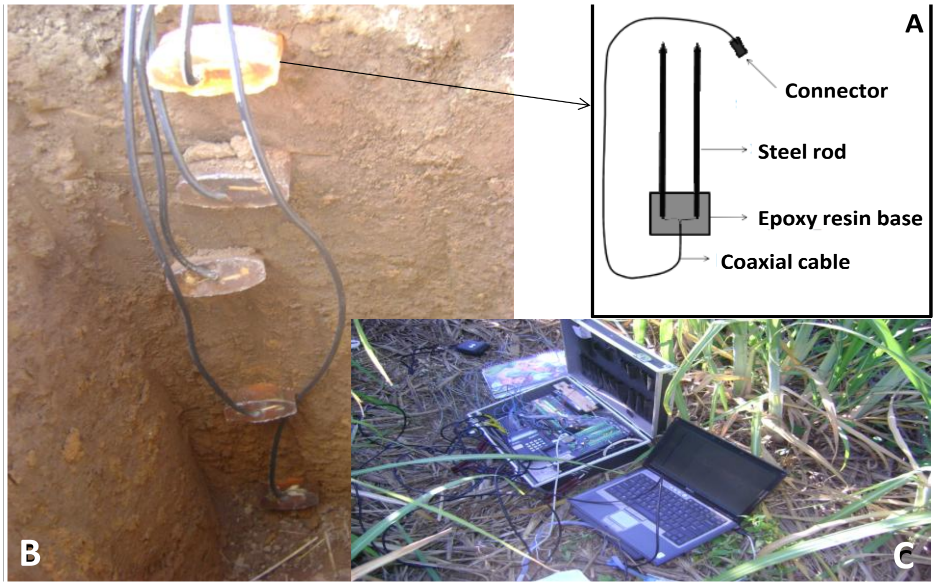


Figure 8. (A) Fabricated soil moisture sensor, (B) installation, and (C) soil volumetric moisture data measurement and download.

2. Soil water storage

The soil water storage for a given layer, *i*, is given as:

$$SWS_{i_t} = \theta_{i_t} * d_i \text{……...…………………...…....………….....7}$$

where SWS_{i_t} is the water stored, mm; θ_{i_t} is the soil volumetric moisture content, cm^3 cm^{-3}; d is the thickness of i^{th} layer, mm; and *t* is the time (day of measurement).

Thus, the total water store, $SWS_t$for a given soil profile during each measurement campaign is given as:

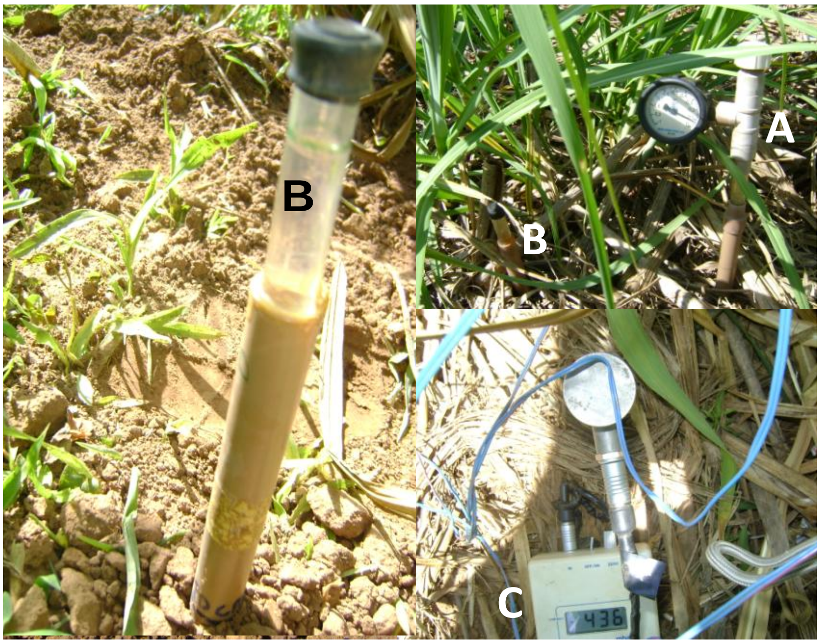
$$SWS_t = \sum_{i=1}^{n} SWS_{i_t} \text{…...8}$$

3. Soil matric potential monitoring

Soil matric potential was also measured alongside TDR readings, using puncture-type tensiometers, installed at 10, 20 and 50 cm Soil matric potential was read manually using a digital-type tensimeter. Vacuum-type tensiometer was also installed to cross-check the readings from the fabricated tensiometers (Figure 9).

4. Soil temperature

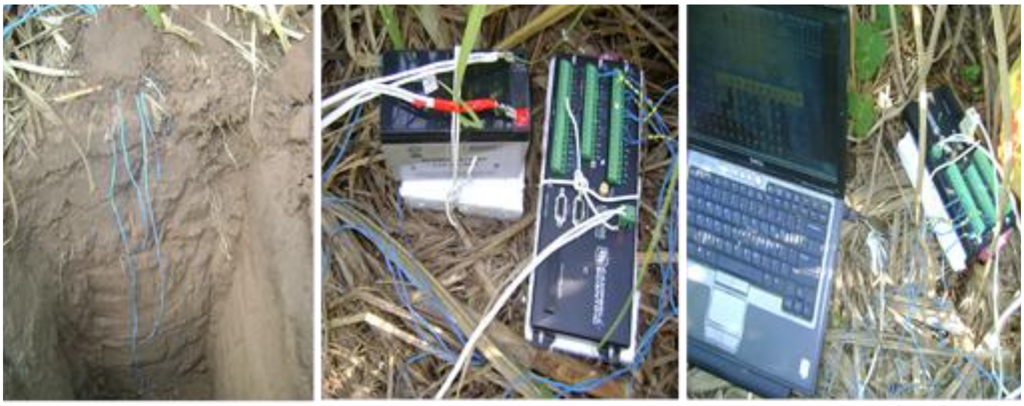
To study the effect of residue mulching on temporal variability of soil temperature, thermocouple soil temperature sensors were installed at soil depths 2.5, 7.5, 15, 30 and 50 cm, representing soil layers 0-5, 5-10, 10-20, 20-40 and 40-60 cm, respectively (Figure 10). Dataloggers (Model: CS 1000, Campbell Equipment Inc., USA) were installed to record and store data automatically at every 30 minutes interval.



A: Vacuum-type tensiometer; B: Puncture-type tensiometer; C: Digital tensimeter

Figure 9. Tensiometers to monitor soil matric potential during the growing seasons in the sugarcane field.

A: Puncture-type tensiometers; B: Digital tensimeter; C: Tung plant



Installation of temperature sensors

Automatic data storage

Data download

Figure 10. Installation of thermocouple soil temperature sensors and measurement of soil temperature in the sugarcane field.

5. Weather data and evapotranspiration

Weather data comprising minimum and maximum temperature, mean relative humidity, wind speed, sunshine hours and precipitation were recorded on daily basis from an automatic weather station located about 1 km from the experimental site. A rain gauge was also installed at the center of the field to confirm the precipitation data from the weather station.

The daily potential evapotranspiration, ET_o, was computed using FAO$-ET_o$ Calculator software, based on Penman-Montieth approach. The detail of the calculations is available in Allen et al. (1998).

Thus, the crop evapotranspiration, ET_c, is given as:

$$ET_c = K_s . K_c \ x \ ET_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

where K_s is the stress reduction coefficient and K_c is the crop coefficient depending on the crop growth stage. In this area, rainfall is adequately distributed throughout the year and there was no stress condition during the growing seasons, hence $K_s = 1$.

Because of the difficulty of determining the crop coefficient (K_c), the K_c values for the different crop growth stages of sugarcane were taken from literature. Thus, the crop coefficient and the respective growth stage for sugarcane were taken from FAO guidelines for computing crop water requirement (FAO Paper No. 56) (Table 2).

Table 2. Single crop coefficients and lengths of crop development stages for sugarcane grown in sub-humid tropical climate.

Stages	Initial	Development	Mid-season	Late season
	Lengths of crop development stages, days			
	30	50	180	60
	Crop coefficients (no units)			
K_c	0.40	-	1.25	0.70

Source: Allen et al. (1998).

The daily simple crop coefficient, K_c, was computed on the assumption that it is constant during the initial and mid-season growing stages while it increases linearly during the developmental stage and decrease linearly during the late season (SILVA et al., 2012) according to the equation:

$$K_{c_t}(dev\ or\ late) = K_{c_{prev}} + \left[\frac{t - \sum L_{prev}}{L_{stage}}\right] . \left[K_{c_{next}} - K_{c_{prev}}\right] \ldots\ldots\ldots\ldots 10$$

where $K_{c_i}(dev\ or\ late)$ is the K_c value on day *t* during the developmental or late stage; $K_{c_{prev}}$ is the K_c value at the end of the previous stage; $K_{c_{next}}$ is the K_c value at the beginning of the next stage, t is the day number within the growing season; L_{stage} is the length of the stage under consideration and $\sum L_{prev}$ is the sum of the lengths of all previous stages.

6. Sugarcane yield

An area, 2 m x 2 m, was demarcated in the sugarcane field to determine crop yield at harvest, and the yield was converted to ton/ha.

3.2.4.3 Soil quality evaluation

1. Principal component analysis and minimum data selection (MDS)

The principal component analysis (PCA) was used to identify the most appropriate indicators to represent land capability (site potential) under different soil and residue management practices from the list of indicators evaluated (Table 3). Component factors comprising the soil quality variables were extracted with eigenvalues greater than one.

Eigenvalues, the amount of variance explained by each factor, were used to categorize and select PC factors. Factors with eigenvalues > 1 explained higher total variation in the data than individual soil variables, while factors with eigenvalues < 1 explained less total variation than each soil variable. Therefore, only PC factors with eigenvalues > 1 were selected and retained for interpretation as soil quality factors. The selected PC factors were subjected to Varimax rotation, the redistribution of the variance of each factor to maximize the relationship between the orthogonal soil variables.

To select indicators within each selected PC factor, indictors with high factor loading rates, within 15% of the highest factor loading were picked for the minimum data set.

However, when more than one variable was retained within a PC factor, correlation was performed to determine if any variable is redundant, and thus the variable with highest correlation sum was considered. Each selected indicator also has communality value which is the portion of the variance being explained by the factors. A soil variable with high communality value shows that a high proportion of its variance is explained by the factor. On the other hand, a low communality value is an indication that much of that variable’s variance remains unexplained. According to Xu et al. (2006), less important should be ascribed to soil variables with low communality values when discussing PC factors. The relative important of a given variable was also considered during the selection process.

2. Integration of indicators to soil quality indices (SQI)

To compute the soil quality indices under the different management practices, three steps were followed, namely: indicator transformation, weight determination and integration of all indicators into a SQI value. For soil attributes measured seasonally, changes in the SQI will

Table 3. Limiting factors, potential indicators and associated management functions used for the study.

Limiting factor	SQ indicator	Associated management function
Organic matter	OM*	Resist surface structural degradation
	SOCD	Resist surface structural degradation
Nutrient storage	TN	Plant nutrient supply and productivity
	C/N ratio	Plant nutrient supply and productivity
Water retention and permeation	BD	Water movement and availability
	Ksat	Water movement and availability
	Pt	Water movement and availability
	Ma	Water movement and availability
	Mi	Water movement and availability
	FC	Water movement and availability
	PWP	Water movement and availability
	AWC	Water movement and availability
Compaction	σ_c	Load bearing capacity
	I_c	Susceptibility to compaction

*OM: organic matter, %; Cpool: carbon pool, Mg/ha; TN: total nitrogen, g/kg; C/N: carbon to nitrogen ratio; BD: bulk density, g/cm^3; Ksat: saturated soil hydraulic conductivity, mm/hr; Pt: total porosity, cm^3 cm^{-3}; Ma: macroporosity, cm^3 cm^{-3}; Mi: microporosity, cm^3 cm^{-3}; FC: field capacity, cm^3 cm^{-3}; PWP: permanent wilting point, cm^3 cm^{-3}; AWC: available water capacity, mm; σ_c: pre-compression stress, kPa; I_c: compression index; SQ: soil quality.

indicate whether the soil quality is aggrading, degrading, or sustainable under different soil management practices (BREJDA et al., 2000a, b).

(a) Transformation (scoring) of selected indicators.

After determining the variables for MDS, every selected soil quality indicator was transformed (scored) for inclusion in the soil quality index computation. Two approaches were used to score the MDS:

(a) the linear scoring function was used to transform the variables with established threshold values to a common range between 0.1 and 1 according to *homothetic transformation* equations 10 and 11 (VELASQUEZ et al., 2007):

$$Y = 0.1 + \left(\frac{(X-b)}{(a-b)}\right) * 0.9 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 11$$

$$Z = 1 - \left(\frac{(X-b)}{(a-b)}\right) * 0.9 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 12$$

where Y and Z are values of the variables after transformation; X is the value of the variable to be transformed while a and b are the maximum and minimum threshold values of the variables (Table 4). Equation 11 was used for variables considered as “more is better” in term of soil function, such as soil organic matter; equation 12 was applied for “less is better” variables, such as bulk density; while both equations were used for “optimum is better”, such as sand content.

(b) because there was no established threshold values for the Ma and pre-compression stress, ranking of variables in ascending order for “more is better” or descending order for “less is better” was used (LIEBIG et al., 2001). The variable was considered as “more is better”, thus each value in the group was divided by the highest value, such that the highest value received 1.

(b) Weight determination

The weights can be assigned objectively or subjectively and there are various methods determining the weights. In this study, the weight of each selected indicator in the MDS was determined based on the variance explained by each PC of the PCA results (TESFAHUNEGN, 2014). Each PC explained a certain amount of the variation in the total data set, this provides “weight” for each of the selected variables. The weights of the indicators of each PC were summed and each indicator fraction was normalized for the total weight to become unity (1).

Table 4. Scoring criteria, baseline and threshold limits of soil quality variables used for evaluating soil quality status of both the sugarcane and tung fields at Santa Maria, Brazil.

Variable	Unit	Criteria[1]	BL[2]	LT[3]	UT[4]	OP[5]	LB[6]	UB[7]	Source of limits
BD	g/cm^3	Less	1.4	1.0	1.8	1.2	-	-	Harris et al., 1996; Reichert et al, 2009.
Pt	cm^3 cm^{-3}	Optimum	-	0.2	0.8	0.5	0.4	0.6	Karlen et al., 1994a, b.
FC	cm^3 cm^{-3}	More	0.28	0.15	0.40	-	-	-	Yao et al., 2013.
AW	cm^3 cm^{-3}	More	0.30	0.20	0.58	-	-	-	Gregory et al., 2000.
TN	g/kg	More	1.3	0.5	3.0	-	-	-	Yao et al., 2013.
OM	%	More	2	1	3	-	-	-	Yao et al., 2013.
Cpool	Mg/ha	More	15	6	24	-	-	-	Yao et al., 2013.

OM: organic matter; Cpool: carbon pool; TN: total nitrogen; BD: bulk density; Pt: total porosity; FC: field capacity; AW: available water

[1] Criteria used for scoring soil variables

[2] BL: baseline, soils receives a score of 0.5 and are generally regarded as the minimum target values

[3] LT: lower threshold; soils at or below the threshold values are prone to structural degradation, destabilization, erosion and low productivity; so the scoring value is zero (0).

[4] UT: upper threshold; soils at or above this values have no further effect on productivity or decrease erosion rate; values at and above this level receive a score of one (1.0).

[5] OP: optimum value

[6] LB: lower baseline

[7] UB: upper baseline

(c) Computation of soil quality index (SQI)

After all the selected indicators have been transformed and the respective weights determined, the SQI values was computed using weighted additive index technique, that is, integrating the weights indices and score values of all indicators into a single value, according to the following equation:

$$SQI = \sum_{i=1}^{n} W_i * S_i \quad \ldots\ldots\ldots\ldots\ldots\ldots 13$$

where W_i is the weight index of i^{th} indicator; S_i is the score value of i^{th} indicator ; and n is the total number of indicators. Since W_i and S_i values were normalized from 0 to 1, the computed SQI values also range between 0 and 1. Higher SQI values indicate better soil quality (GLOVER et al., 2000).

3.2.5 Temporal processes of soil water storage and temperature

Time-series analysis was used to evaluate the temporal process of soil water storage (*SWS*) and soil temperature and other soil-atmosphere variables measured in the different treatments at times, t (t = 1,2,3,4……...,n) over 2-year period, 2011/2012 and 2012/2013 growing seasons for the sugarcane experiment.

The state–time analysis characterizes the state of a property (set of p unobservable variables) at a time *t* to its state at a time *t*–k, t=1,2,3,4, ..., n, in this study. For *k*= 1, the state–space approach is described by the equation (or state equation):

$$Z_t = BZ_{t-1} + \omega_t \text{……………………………………………14}$$

where Z_t and Z_{t-1} are the state vectors (a set of q unobservable variables) at times *t* and *t-1*; *B* is an identity *qxq* matrix of state coefficients, which indicates the measure of the regression; ω_t is an observation noise vector, assumed to have zero mean and not correlated as well as normally distributed.

The state coefficients of the matrix q *x* q and noise variances were estimated following the procedure of Shumway and Stoffer (1982). According to Shumway (1988), if theZ_t dataare scaled with respect to their mean (*m*) and standard deviation (σ) as:

$$\mathrm{Z}_t = [Z_t - (m - 2\sigma)]/4\sigma \text{ ……………………………………...15}$$

where Z_t is the measured soil variable at time t; m and σ are the mean and standard deviation of the measured soil variable.

The transformed values of $\mathrm{Z}_t$become dimensionless with mean, μ= 0.5 and standard deviation, δ = 0.25. This transformation allows the state coefficients of matrix B have magnitudes proportional to their contribution to each state variable to be used in the analysis. Finally, the temporal analysis was performed using the software: svar.exe for soil water storage measured at different time interval while Applied Statistical Times Series Analysis (ASTSA) (SHUMWAY, 1988) was used for the automatic soil temperature data. Autocorrelation, cross-correlation and state equations between soil water storage versus precipitation, evapotranspiration and matric potential, as well as soil temperature versus air temperature were generated. The effect of time interval between measurements was evaluated on the temporal covariance structure of soil temperature while the effect of missing data on the performance of ASTSA was evaluated by omitting 25 and 50% of the soil temperature data (with air temperature remained intact).

3.3 Tung-based agroforestry experiment

The tung experiment focused on the effect of agroforestry system on soil quality indicators, water retention and performance of tung in tung-based intercropping and crop rotation system.

3.3.1 Experimental design, treatments, and field management

The tung-based cropping system was laid out in a randomized complete block design (RCBD) with four replications. The cropping system consisted of: tung-crambe-sunflower/soybean + inorganic fertilizer (T-C-S/So+I); tung-crambe-sunflower/soybean + organic fertilizer (T-C-S/So+O); tung-oats-peanut (T-Ot-P); and sole tung (control). Crambe and oats were planted in winter season while peanut and sunflower (1st year)/soybean (2nd year) were planted in summer season. Thus, there are sixteen (16) plots, with two tung stands per plot at a spacing of 10 m and 5 m within and between tung crop rows, respectively, giving a plot area of 50 m^2. On either side of the tung row, a gap of 20 cm was marked while the remaining portion on both sides was used for the intercrops at a spacing of 40 cm (Figure 11).

In the cropping systems that received additional mineral fertilizer (NPK) application, the quantities used were as follows: 15 kg ha^{-1} N; 30 kg ha^{-1} of P_2O_5 and 25 kg ha^{-1} K_2O at sowing of each season, representing urea, triple superphosphate (TSP) and potassium chloride (KCL), respectively. At 56 days after sowing (DAS), 45 kg ha^{-1} of N (urea) was applied as top dressing for T-C-S/So+I (with crambe crop) in winter of 2012, after 63 DAS in summer of

2012/2013 growing season, but with sunflower as the intercrop, and 33 DAS in winter of 2013, with crambe as the intercrop.

In the summer of 2013/2014 growing season, top dressing was not applied in the T-C-S/So+I treatment with soybean as the intercrop. In T-C-S/So+O treatment that received additional application of organic manure, poultry manure (PM) was used. For all the four trials, the poultry manure was obtained from a poultry company based on broiler rearing, with an average of five chickens on a bed of wood shavings. The dry matter (DM); total N and C; and mineral N (ammonium and nitrate) were analyzed according to Tedesco et al. (1995) without pre-drying and presented in Table 5. Weeding was done manually by hoeing and physical removal of unwanted plants.

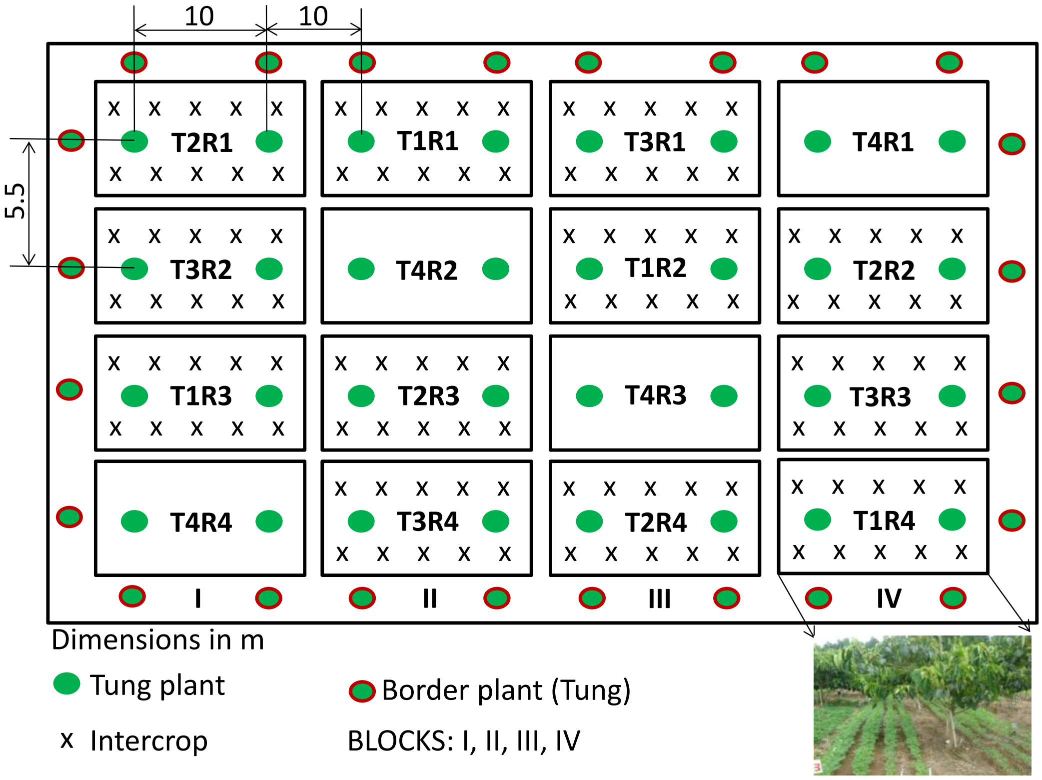


Figure 11. Field layout of the tung-based cropping system at the Experimental Station of the Department of Soils, Federal University of Santa Maria, Brazil. Inset photo shows tung-soybean intercrop (T1R4).

T1: tung-crambe-sunflower/soybean + in-organic fertilizer (TCS/So+I); T2: tung-crambe-sunflower/soybean + organic fertilizer (TCS/So+O); T3: tung-oats-peanut (TOtP); T4: sole tung (control). R1, R2, R3, and R4: replicates.

Table 5. Amount of dry matter (DM) of poultry manure (PM) applied to the T-C-S/So+O treatment of the tung experiment in a single dose (at sowing) and concentrations of some elements during each season.

Treatments[1]	Dose applied	TC	DM	TN	NO_3-NH_3	N-NO_3
	Mg ha^{-1}	%	------------------------Mgha^{-1}			----------------------
CR+PM - 2012	6.6	30	4.4	119.3	38.2	18.6
SU+PM – 2012/2013	6.2	36	3.9	119.7	31.9	16.1
CR+PM – 2013	5.4	29	3.7	119.4	32.1	17.2

[1] CR+PM-2012: crambe + additional poultry manure during winter of 2012; SU+PM-2012/2013: sunflower + additional poultry manure during summer of 2012/2013; CR + PM-2013: crambe +additional poultry manure during winter of 2013

TC: total carbon, %; DM: dry matter, Mgha^{-1}; TN: total nitrogen, Mgha^{-1};, NO_3-NH_3: ammonium nitrate, Mgha^{-1}; N-NO_3 nitrate-nitrogen, Mgha^{-1}.

3.3.2 Soil sampling

Disturbed and undisturbed soil samples were collected using cores (with a volume of about 102 cm^3 for physical properties in the middle of 0-10, 10-20, 20-40 40-60 and 60-80 cm soil layers. Soil sampling was made at initial and every year (at harvest). Samples were kept in sealed plastic cases and transported to the laboratory for analysis. Where necessary, samples were kept in the refrigerator to minimize moisture lost.

3.3.3 Soil texture and chemical properties of the tung field

Soil samples were collected before imposing intercropping treatments and were analyzed for both soil chemical properties and particle size distribution. The chemical properties are shown in Table 6 while the average sand, silt and clay contents as well as the texture of the soil layers of the experimental field are presented in Figure 12. The textural classes of the tung field varied, with higher clay content (up to 44%) in the subsurface layers

Table 6. Some soil chemical properties of the tung field, Department of Soils Experimental Station, Santa Maria, Brazil.

	pH	P	K	Ca	Mg	Al	H+Al	ECEC	CEC $pH_{7.0}$	Sum of	Saturation	
Soil layer, cm	**H_2O**	---mg dm^{-3}---		----------	----------	----- $Cmol_c$	dm^{-3} -----	----------	----------	**base**	**Al**	**Base**
0-10	6.0	29.0	108.0	5.0	1.8	0.0	2.8	7.1	9.9	6.4	0.0	72.2
10-20	6.0	12.6	64.0	4.3	2.0	0.0	2.8	6.5	9.3	6.4	0.0	69.7
20-40	5.8	3.0	36.0	1.9	0.9	3.8	2.4	6.7	10.4	4.4	0.0	69.5
40-60	5.9	3.7	52.0	2.1	1.2	4.8	2.5	8.2	9.8	4.2	0.0	68.9
60-80	5.7	3.0	40.0	1.9	0.9	5.4	2.3	8.3	11.5	4.0	0.0	66.2

pH: level of acidity or alkalinity; P: phosphorus, K: potassium, Ca: calcium, Al: Aluminum, H+AL: acidity, ECEC: Effective cation exchange capacity, $CEC_{pH7.0}$: buffered cation exchanged capacity, Al: aluminum.

compared with the sugarcane field. The 0-10 cm surface layer has sandy loam texture, 10-20 and 20-40 cm layers are sandy loam, loam or sandy clay loam texture while the 40-60 and 60-80 cm deeper layers are clay loam to clay texture (Figure 12).

3.3.4 Evaluations

3.3.4.1 Laboratory analysis

1. Soil texture

The granulometric analysis of the and tung field was determined by the pipette method, using 20g of air-dried soil samples that have passed through 2-mm sieve and sodium hydroxide (NaOH) solution (10% v/v) as the dispersing agent, following the procedure outlined in EMBRAPA (2011) to quantify the clay (<0.002 mm), (0.002-0.05 mm), and sand (0.05-2.0 mm) content while the textural class for each soil depth was obtained using the textural triangle of the USDA (as shown in Figure 12).

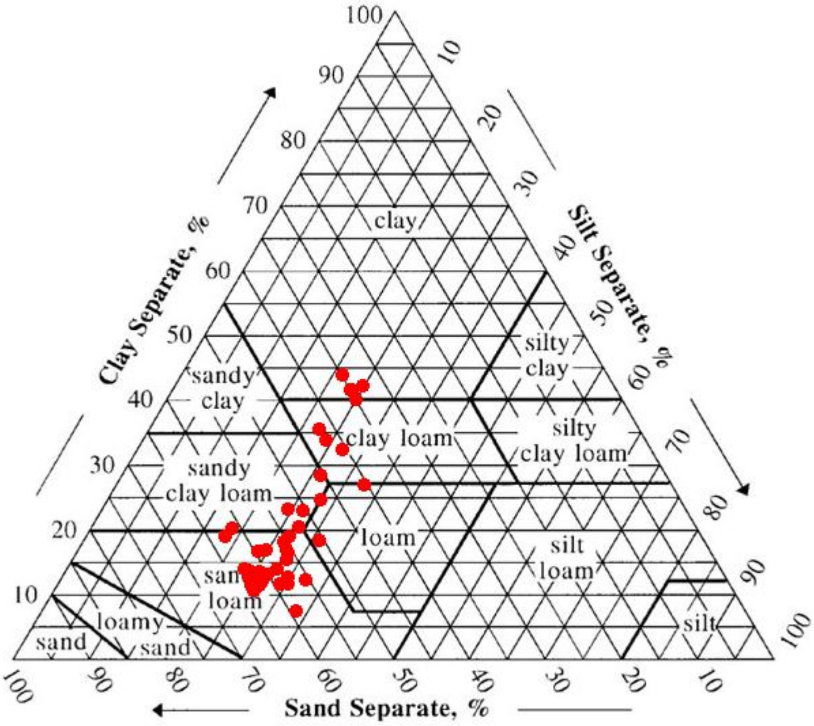


Figure 12. The average sand, silt and clay contents as well as the texture of the 0-10, 10-20, 20-40, 40-60 and 60-80 cm soil layers of the tung field at Santa Maria, southern Brazil.

The red circles indicate the texture.

2. Soil physical properties

Soil physical properties such as bulk density, degree of compaction, total porosity, macro- and microporosity, field capacity, permanent wilting point and maximum available were evaluated following the standard procedures already described under sugarcane experiment.

3. Saturated hydraulic conductivity

The saturated hydraulic conductivity (Ksat) was determined by the constant-head permeameter (KLUTE and DIRKSEN, 1986) (Figure 13), on undisturbed soil samples collected in metal cylinders (of known volume) after saturation by capillarity in a water bath for 48 hours. The determination of Ksat was performed by collecting and measuring the amount of water that percolates through the soil sample under a constant hydraulic head of 3 cm in the water column according to the methodology described by Embrapa (2011). From the data, the Ksat was calculated according to Equation 3.

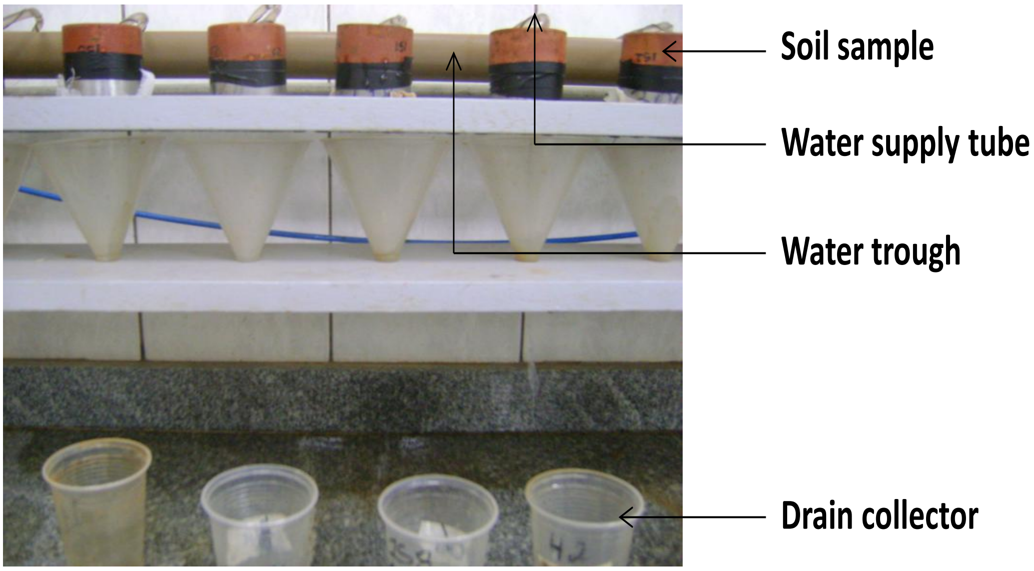


Figure 13: Setup for saturated hydraulic conductivity (K_{sat}) test by constant-head permeameter method. (KLUTE and DIRKSEN, 1986).

$$Ksat = \frac{Q*L}{A*H*t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

where K_{sat} is saturated hydraulic conductivity, cm/hr; Q is the volume of water that flow through the soil column in a given time, cm^3; L is the length of the soil column, cm; H is the total water head above the soil column, cm; A is the area the soil column, cm^2, t is the time, hr.

4. Soil organic matter, total nitrogen, C/N ratio and carbon pool

These variables were also evaluated following the laboratory procedures described under sugarcane experiment.

3.3.4.2 Field measurements

1. Soil moisture content monitoring

In the tung agroforestry system, TDR sensors were installed close to tung and 1 m from tung (intercrop rows) at 0-10, 10-20, 20-40, 40-60 and 60-80 cm soil depths. In each plot, 10 TDR sensors (5 sensors close to tung plant and 5 sensors) were installed, with a total of 160 sensors for the entire field. Likewise, soil moisture monitoring during the growth cycle was read manually at different time intervals, ranging from daily, 2, 5 days; 1 or 2 weeks by connecting the soil moisture sensors to time domain reflectometry (TDR) datalogger (TDR 100, Campbell Equip. Inc., USA). The calibration equation developed for the sugarcane field (KAISER et al., 2010) was used as the soil type is the same.

2. Soil water storage

The soil water storage for each soil layer and total profile water retention were calculated according to the procedure described under sugarcane experiment.

3. Tung plant height

Tung plant height was measured at the beginning in 2012 and at harvest of 2012/2013 and 2013/2014 growing seasons. Plant height from the soil surface to the tip of the last bud was initially measured using a standard measuring tape, after the second year, the height was determined using vertex and transponder (Model: Vertex IV & Transponder T3, HAGLOF SWEDEN AB) according to the methodology described by Alberta (2012). The description of the equipment can be found in the manufacturer`s website: http://www.haglofcg.com.

3.3.4.3 Soil quality evaluation

The seasonal pattern of soil quality status of the tung-based agroforestry system was evaluated following the procedures presented under the sugarcane experiment above.

3.4 Statistical analysis

The results were tested for normality using homogeneity of variances by the Bartlett's test ($p > 0.05$). Multivariate analysis of variance (MANOVA) by F-test ($p < 0.05$) of the soil variables was carried out, and Post-Hoc test was used to separate means while the effects of tillage (T), mulching (M) and cropping (C) as well as the interaction between tillage (T) x residue mulch (M)on soil variables, soil quality index, soil water retention, tung plant height, and sugarcane yield were evaluated using Fisher's least significant difference (LSD) test. Analysis of variance (ANOVA) and linear and multiple regression were conducted to determine the relationships between selected soil quality indicators, soil quality index and management goals of soil water retention, plant growth and yield. All the statistical analyses were done using SPSS (*SPSS IBM Statistics v. 20*).

4 RESULTS

4.1 Sugarcane experiment

4.1.1Rainfall pattern and potential evapotranspiration

The temporal distribution of the daily rainfall (P) and evaporative demand of the atmospheric (potential evapotranspiration, ETp) during the three sugarcane growing seasons is shown in Figure 14 while Table 7 shows the total monthly P and ETp values. Rainfall was well distributed during the growing seasons, except in December of 2011 when rainfall was very low, while the daily potential evapotranspiration followed the course of daily climatic conditions.

The total monthly P ranged between 49 and 166 mm in 2010/2011 growing season, between 13 and 184 mm in 2011/2012 growing season, while the values were between 72 and 293 mm in 2012/2013 growing season. The total seasonal rainfall received were 1204, 1001, and 1639 mm for 2010/2011, 2011/2012, and 2012/2013 growing seasons, respectively, with the highest and lowest total seasonal rainfall amount in 2012/2013 and 2011/2012 seasons, respectively.

The total monthly ETp values ranged between 15 and 169 mm during 2010/2011 growing season, with the total monthly P values lower than ETp in the months of October, November and December 2010 as well as January 2011. In 2011/2012 season, the values of the total monthly ETp were between 10 and 179 mm, with the total monthly P values lower than ETp in the months of September, November and December 2011 as well as January and February 2012. For the 2012/2013 growing season, total monthly ETp values ranged from35 to 152 mm and the total monthly P values lower than ETp in the months of November 2012 as well as January, March and May 2013. The total seasonal values of ETp were 974, 1057, and 868 mm for 2010/2011, 2011/2012 and 2012/2013 growing seasons, respectively. Comparing the total seasonal values of P and ETp, ET_p was lower than P amount in each season (Table 7).

Table 7. Total monthly precipitation and evaporative demand (potential evapotranspiration) during the 2010/2011, 2011/2012, and 2012/2013 sugarcane growing seasons at Santa Maria, southern Brazil.

	2010/2011		2011/2012		2012/2013	
	P	ETp	P	ETp	P	ETp
Month	mm					
Sep	-	-	61	68	173	47
Oct	49	100	185	99	255	90
Nov	71	134	42	150	73	146
Dec	158	169	13	175	293	149
Jan	127	151	69	179	145	152
Feb	166	108	135	120	98	105
Mar	55	95	151	96	189	101
Apr	165	45	109	40	147	109
May	55	18	138	19	72	87
Jun	99	16	35	19	81	35
Jul	163	17	63	10	114	35
Aug	96	15	-	-	-	-
Total	**1204**	**868**	**1001**	**975**	**1640**	**1056**

ETp: potential evapotranspiration, mm; P: precipitation, mm.

4.1.2 Effect of tillage and crop residue mulching on soil quality indicators

1 Bulk density and porosity

The results of the initial and seasonal values of soil bulk density (BD) of the 0-10, 10-20 and 20-40 cm layers are presented in Table 8. Generally, there was increase in average BD values with depth until 40 cm layer.

At initial (2010), the averages value of BD for the 0-10 cm surface layer was between 1.53 and 1.66 g/cm^3 and the effect of tillage was not significant ($p<0.05$). For the 2010/2011 growing season, BD had values between 1.59 and 1.71 g/cm^3 and no tillage treatment had significant effect on the BD. For 2011/2012 growing season, similar statistical result was

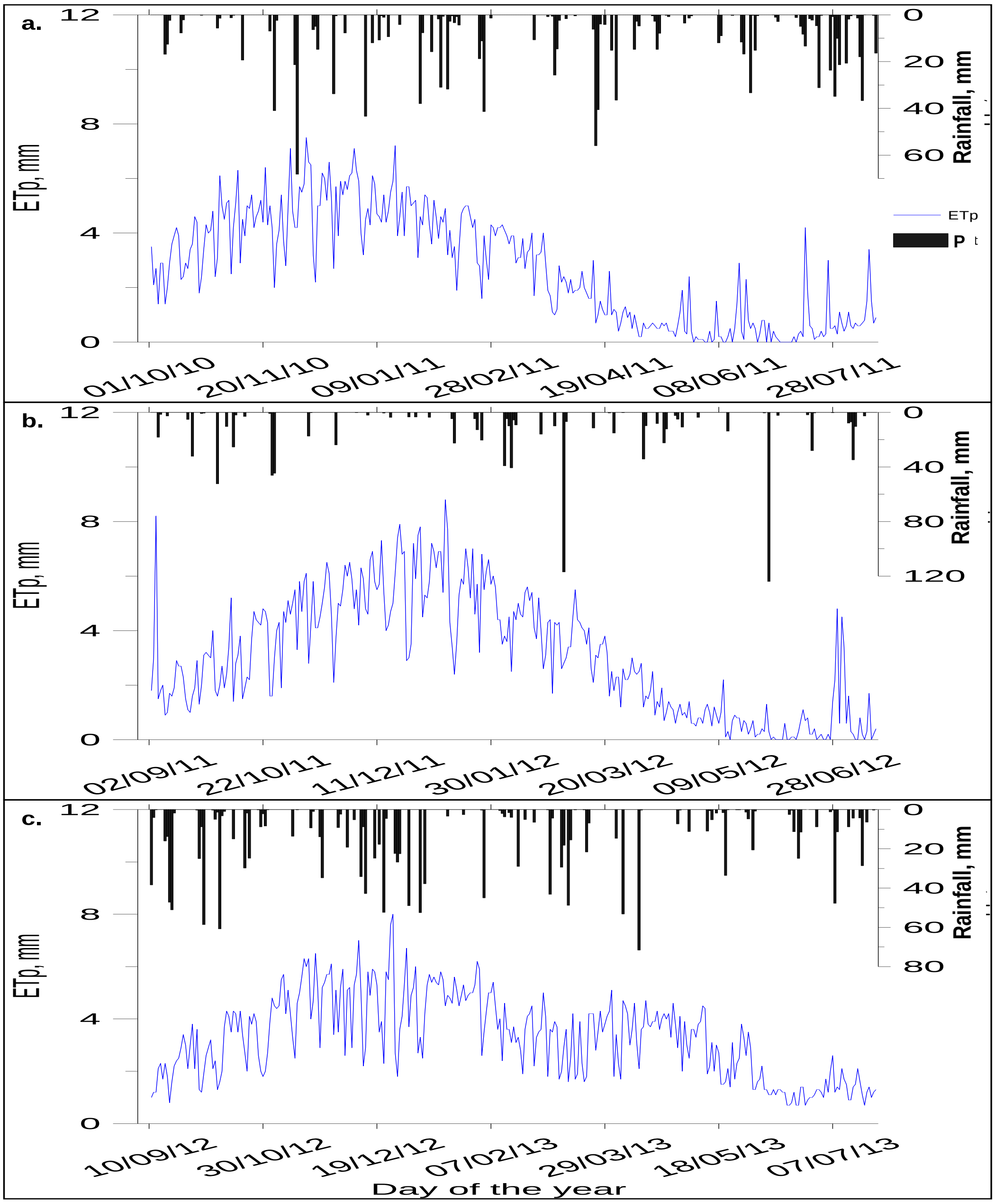


Figure 14. Temporal variability of precipitation and evaporative demand (potential evapotranspiration) during the (a) 2010/2011, (b) 2011/2012, and (c) 2012/2013 sugarcane growing seasons at Santa Maria, southern Brazil.

ET_p: environmental demand (potential evapotranspiration), mm

P: rainfall, mm

obtained, with average BD values ranging between 1.52 and 1.64 g/cm^3. For the 2012/2013 growing season there was no significant difference in the average BD among the tillage

Table 8. Soil bulk density of the different soil layers and treatments at initial (2010) and at harvest of three consecutive sugarcane growing seasons at Santa Maria, southern Brazil.

	Treatments						Effect		Interaction
Soil depth, cm	NT	NTC	Chi	CT	M	NM	T	M_e	T x M
	2010 (Initial)§								
0-10	1.64	1.66	1.53	1.53	-	-	0.64^{ns}	-	-
10 -20	1.70	1.73	1.79	1.75	-	-	0.53^{ns}	-	-
20-40	1.67	1.75	1.74	1.78	-	-	1.35^{ns}	-	-
40-60	1.69	1.66	1.65	1.71	-	-	1.12^{ns}	-	-
	2010/2011 growing season§								
0-10	1.59	1.64	1.71	1.61	-	-	0.57^{ns}	-	-
10 -20	1.64	1.65	1.62	1.63	-	-	0.63^{ns}	-	-
20-40	1.67	1.71	1.59	1.66	-	-	1.46^{ns}	-	-
40-60	1.66	1.61	1.65	1.59	-	-	1.06^{ns}	-	-
	2011/2012 growing season								
0-10	1.59	1.64	1.52	1.54	1.56	1.58	1.86^{ns}	0.38^{ns}	1.20^{ns}
10 -20	1.67	1.72	1.64	1.66	1.67	1.68	0.65^{ns}	0.08^{ns}	0.48^{ns}
20-40	1.69	1.72	1.66	1.78	1.69	1.71	4.92*	0.84^{ns}	3.00^{ns}
40-60	1.60	1.66	1.62	1.67	1.63	1.65	1.71^{ns}	0.55^{ns}	0.07^{ns}
	2012/2013 growing season								
0-10	1.44	1.59	1.49	1.46	1.48	1.54	2.79^{ns}	0.27^{ns}	0.40^{ns}
10 - 20	1.66	1.77	1.58	1.68	1.68	1.67	6.06*	0.18^{ns}	0.07^{ns}
20-40	1.69	1.78	1.64	1.71	1.71	1.71	6.58*	0.26^{ns}	0.65^{ns}
40-60	1.60	1.66	1.62	1.65	1.63	1.63	0.87^{ns}	0.03^{ns}	0.36^{ns}

NT: no-tillage; NTC: compacted no-tillage; Chi: Chiseling tillage; CT: conventional tillage; M: residue mulching; NM: no mulching; T: tillage effect; M_e: mulching effect.

*significant; and ns: not significant at 5% probability level by LSD.

§data collected by Fontanela (2012).

treatments, although the BD values were slightly lower (between 1.44 and 1.59 g/cm^3) compared to the initial values.

For other soil layers, average BD values were between 1.58 and 1.79 g/cm^3, with the highest BD (as high as 1.79 g/cm^3) values obtained in the 10-20 cm layer. For these layers, there was no discernible trend in the values of BD over the seasons. The statistical analysis showed that the effect of tillage was significant ($p<0.05$) in the 10-20 cm layer only at harvest of 2011/2012 growing season while the effect was significant ($p<0.05$) in the 20-40 cm layer at harvest of both 2011/2012 and 2012/2013 growing seasons. For the 40-60 cm layer, tillage effect was not significant (Table 8).

Regardless of tillage, residue mulching did not significantly ($p<0.05$) influence BD for all the soil layers and the two seasons evaluated. For the 0-10 cm surface layer that received residue mulch, the average values of BD was at par (1.56 g/cm^3 vs 1.58 g/cm^3) at harvest of 2011/2012 season growing. For the 2012/2013 growing season, very little difference was observed in the average value of BD between mulched (1.48 g/cm^3) and no mulch (1.54 g/cm^3) treatments. In addition, there was no significant ($p<0.05$) interaction between tillage and mulching treatments on BD during the two years of evaluation (Table 8).

Total porosity (Pt) did not differ significantly ($p<0.05$) under the different management practices of tillage and mulching and in all the soil layers (Table 9) and generally decreased down to 40 cm layer.

At initial (2010), the average values of Pt in the 0-10 cm surface layer ranged between 0.37 and 0.43 cm^3 cm^{-3}, with tilled treatments (Chi and Chi) having slightly higher value compared with no tilled treatments (NT and NTC). In the sub-surface layers, average values of Pt were almost at par. In subsequent seasons, inconsistent results were obtained regarding tillage methods. At harvest of 2010/2011 growing season, Pt was at par (about 0.30 cm^3 cm^{-3}) for all treatments. In 2011/2012 season, Pt was about 0.40 cm^3 cm^{-3} for NT, Chi and CT treatments and about 0.30 cm^3 cm^{-3} for NTC treatment. While at harvest of 2012/2013 growing season, Pt of the 0-10 cm surface layer was almost the same (0.40 cm^3 cm^{-3}). For the subsurface layers, average Pt values were lower and similar for all treatments (Table 9).

Irrespective of tillage method, residue mulching had no significant ($p<0.05$) effect on Pt for all the soil layers and at harvest of both 2011/2012 and 2012/2013 growing seasons. For the 0-10 cm surface layer, the average values of Pt were at par, 0.35 cm^3 cm^{-3} and 0.39 cm^3 cm^{-3} for 2011/2012 and 2012/2013 growing seasons, respectively. For other soil layers, the average values of BD were also at par.

Except in the 0-10 cm surface layer in 2012/2013 growing season, macroporosity (Ma) was not significantly ($p<0.05$) affected by tillage (Table 9). Likewise, Ma decreased with soil depth down to 40 cm and increased in the 40-60 cm deeper layer. At initial (2010), average values of Ma in the 0-10 cm surface layer were high, ranging between 0.13 and 0.18 cm^3 cm^{-3}. In 2010/20011 growing season, the average values of Ma decreased, ranging between 0.06 and 0.09 cm^3 cm^{-3}, while at harvest of 2011/2012 and 2012/2013 growing seasons, the values of Ma in this surface layer increased, with values ranging between 0.09 and 0.18 cm^3 cm^{-3}.

In both 10-20 and 20-40 cm layers with higher BD values, the average values of Ma decrease was as low as 0.05 cm^3 cm^{-3} and not more than 0.10 cm^3 cm^{-3} with respect to initial

Table 9. Total porosity (Pt), macroporosity (Ma), and microporosity (Mi) of the different soil layers and treatments during three consecutive sugarcane growing seasons at Santa Maria, southern Brazil.

	Pt, cm^3 cm^{-3}				Ma, cm^3 cm^{-3}				Mi, cm^3 cm^{-3}			
	0-10	10 20	20-40	40-60	0-10	10 20	20-40	40-60	0-10	10 20	20-40	40-60
	Soil layer, cm											
Trt	Initial (2010) [§]											
NT	0.38	0.36	0.37	0.36	0.14	0.12	0.13	0.14	0.24	0.24	0.24	0.22
NTC	0.37	0.31	0.34	0.38	0.13	0.10	0.10	0.14	0.24	0.21	0.24	0.24
Chi	0.43	0.36	0.34	0.38	0.17	0.12	0.10	0.14	0.26	0.24	0.24	0.24
CT	0.42	0.34	0.33	0.36	0.18	0.09	0.08	0.12	0.24	0.25	0.25	0.24
T	1.23^{ns}	1.18^{ns}	0.82^{ns}	0.60^{ns}	1.31^{ns}	0.67^{ns}	1.34^{ns}	0.67^{ns}	0.82^{ns}	0.74^{ns}	0.80^{ns}	0.53^{ns}
	2010/2011 growing season[§]											
NT	0.34	0.33	0.33	0.32	0.09	0.07	0.07	0.07	0.25	0.26	0.25	0.25
NTC	0.34	0.33	0.31	0.34	0.07	0.07	0.05	0.08	0.27	0.26	0.26	0.25
Chi	0.31	0.33	0.34	0.33	0.06	0.08	0.10	0.08	0.25	0.25	0.25	0.26
CT	0.34	0.33	0.33	0.36	0.07	0.07	0.07	0.09	0.27	0.26	0.25	0.26
T	0.73^{ns}	0.38^{ns}	0.35^{ns}	0.63^{ns}	0.37^{ns}	0.69^{ns}	1.26^{ns}	0.78^{ns}	1.03^{ns}	0.57^{ns}	0.74^{ns}	0.65^{ns}
	2011/2012 growing season											
NT	0.35	0.29	0.30	0.33	0.11	0.05	0.06	0.11	0.24	0.24	0.24	0.22
NTC	0.33	0.29	0.29	0.31	0.09	0.05	0.05	0.09	0.24	0.24	0.24	0.22
Chi	0.37	0.32	0.30	0.32	0.15	0.07	0.06	0.10	0.22	0.25	0.24	0.22
CT	0.36	0.31	0.29	0.31	0.11	0.06	0.05	0.08	0.25	0.25	0.24	0.23
M	0.35	0.30	0.29	0.32	0.12	0.06	0.05	0.09	0.23	0.24	0.24	0.23
NM	0.35	0.31	0.29	0.32	0.11	0.05	0.05	0.10	0.24	0.26	0.24	0.22
T	1.33^{ns}	1.09^{ns}	0.74^{ns}	1.82^{ns}	0.39^{ns}	0.74^{ns}	1.42^{ns}	1.83^{ns}	1.14^{ns}	0.33^{ns}	0.80^{ns}	0.51^{ns}
M_e	0.01^{ns}	0.48^{ns}	0.09^{ns}	0.32^{ns}	1.37^{ns}	0.47^{ns}	0.20^{ns}	3.03^{ns}	3.89^{ns}	1.27^{ns}	0.09^{ns}	2.20^{ns}
T x M	0.95^{ns}	1.03^{ns}	0.90^{ns}	0.63^{ns}	0.27^{ns}	0.27^{ns}	1.05^{ns}	0.20^{ns}	1.14^{ns}	0.80^{ns}	1.62^{ns}	1.50^{ns}
	2012/2013 growing season											
NT	0.40	0.30	0.31	0.33	0.15	0.06	0.07	0.10	0.25	0.24	0.24	0.23
NTC	0.36	0.29	0.30	0.33	0.11	0.05	0.06	0.11	0.25	0.24	0.24	0.22
Chi	0.39	0.30	0.32	0.35	0.13	0.06	0.09	0.13	0.26	0.24	0.23	0.22
CT	0.41	0.29	0.32	0.32	0.18	0.05	0.08	0.09	0.23	0.24	0.24	0.23
M	0.39	0.29	0.31	0.34	0.14	0.05	0.07	0.11	0.25	0.24	0.24	0.23
NM	0.38	0.29	0.31	0.33	0.11	0.05	0.08	0.11	0.27	0.24	0.23	0.22
T	2.69^{ns}	0.74^{ns}	3.36^{ns}	2.42^{ns}	3.44*	1.42^{ns}	1.68^{ns}	2.64^{ns}	1.56^{ns}	0.80^{ns}	1.63^{ns}	1.18^{ns}
M_e	0.44^{ns}	0.09^{ns}	0.01^{ns}	0.15^{ns}	1.17^{ns}	0.20^{ns}	1.31^{ns}	0.001^{ns}	0.63^{ns}	0.09^{ns}	1.17^{ns}	0.30^{ns}
T x M	0.86^{ns}	0.90^{ns}	1.61^{ns}	1.89^{ns}	0.47^{ns}	1.05^{ns}	2.65^{ns}	2.53^{ns}	0.29^{ns}	1.62^{ns}	1.11^{ns}	0.65^{ns}

Trt: treatment; NT: no-tillage; NTC: compacted no-tillage; Chi: Chiseling tillage; CT: conventional tillage; T: tillage effect; M: residue mulching; NM: no mulching; M_e: mulching effect; T x M: tillage x mulching interaction; *significant; and ns: not significant at 5% probability level by Least significant difference (LSD).

[§] data collected by Fontanela (2012).

values. Similar reduction in average Ma values was obtained for the 40-60 cm layer, however, they were slightly higher in 2011/2012 and 2012/2013 growing seasons compared with the reduction recorded at harvest of 2010/2011 growing season.

Regardless of tillage method, surface residue mulching application had no significant effect on Ma, however it increased the average seasonal values. In the 0-10 cm surface layer, the magnitude of Ma was at par (about 0.12 cm^3 cm^{-3}) for all treatments at harvest of 2011/2012 growing season and up to 0.14 cm^3 cm^{-3} at the end of 2012/2013 growing season (Table 9).

Microporosity was not significantly ($p<0.05$) influenced by tillage at the beginning and in all the three seasons and for all the soil depths (Table 8).The average seasonal values of Mi were almost at par for the different tillage methods and all the soil layers for each growing season, however, treatments with high Ma values had lower values of Mi and vice versa.

Regardless of tillage method, residue mulching had no significant effect ($p<0.05$) on Mi for all the soil layers and the two seasons of evaluation, however average Mi values ranged from 0.22 to 0.27 cm^3 cm^{-3} . Similarly, tillage and residue mulching did not have any significant ($p<0.05$) interaction on total porosity, macroporosity and microporosity over the two seasons evaluated (Table 9).

2 *Field capacity, permanent wilting point and maximum available water*

The distribution of average soil volumetric water content at field capacity (FC), permanent wilting point (PWP) and maximum available water content for root extraction (AW) for the different soil layers of the sugarcane field under different management practices is shown in Figures 15, 16 and 17. Different behaviour was observed as regard soil water content at FC in the different soil layer in each season (Figure 15).

Average values of soil water content at FC did not differ significantly ($P<0.05$). At initial (2010), the average soil water content at FC of the 0-10 cm soil depth ranged between 0.21 and 0.24 cm^3 cm^{-3}. For the 10-20 m layer, the FC values were similar to that of surface layer in all seasons. For other deeper layers, the FC values were virtually the same (Figure 15). Irrespective of tillage method, residue mulching did not significantly influence the water content at field capacity (Figures 16 and 17).

Similarly, the average soil water content at PWP was significant ($p<0.05$) affected by tillage only in the 10-20 cm soil layer during the 2012/2013 growing season. At initial (2010),

Table 10. Average values of maximum available water (AWmax) of the 0-10, 10-20,20-40 and 40-60 cm soil layers of the sugarcane field under different tillage methods and residue mulching at initial in 2010 and at harvest of 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, southern Brazil.

Soil depth, cm	NT	NTC	Chi	CT	T_e	NM	M	M_e
	2010 (initial)§							
0-10	0.16	0.17	0.14	0.16	0.53^{ns}	-	-	-
10-20	0.15	0.16	0.15	0.17	0.47^{ns}	-	-	-
20-40	0.15	0.15	0.15	0.15	0.18^{ns}	-	-	-
40-60	0.15	0.15	0.15	0.16	0.51^{ns}	-	-	-
	2010/2011 growing season§							
0-10	0.16	0.18	0.16	0.17	2.41^{ns}	-	-	-
10-20	0.18	0.18	0.16	0.17	1.76^{ns}	-	-	-
20-40	0.17	0.17	0.16	0.17	1.01^{ns}	-	-	-
40-60	0.16	0.17	0.17	0.18	1.15^{ns}	-	-	-
	2011/2012 growing season							
0-10	0.16	0.14	0.15	0.13	1.96^{ns}	0.15	0.15	1.10^{ns}
10-20	0.13	0.16	0.14	0.14	0.96^{ns}	0.14	0.14	0.002^{ns}
20-40	0.13	0.14	0.13	0.14	0.60^{ns}	0.14	0.14	2.54^{ns}
40-60	0.13	0.13	0.11	0.13	0.97^{ns}	0.13	0.14	3.95^{ns}
	2012/2013 growing season							
0-10	0.16	0.14	0.16	0.14	1.66^{ns}	0.15	0.16	0.63^{ns}
10-20	0.15	0.14	0.15	0.14	0.74^{ns}	0.14	0.15	4.53^{ns}
20-40	0.14	0.14	0.15	0.14	1.18^{ns}	0.14	0.15	1.12^{ns}
40-60	0.14	0.13	0.14	0.14	$1. 24^{ns}$	0.14	0.14	0.50^{ns}

NT: no-tillage; NTC: compacted no-tillage; Chi: Chiseling tillage; CT: conventional tillage; T_e: tillage effect; M: residue mulching; NM: no mulching; M_e: mulching effect

*significant; and ns: not significant at 5% probability level by Least significant difference (LSD).

§data collected by Fontanela (2012).

the average soil water content at PWP was unique for all layers, 0.07 cm^3 cm^{-3}, however with time, average values in the different layers varied and increased slightly, ranging between 0.07and 0.09 cm^3 cm^{-3} (Figure 15). Similarly, residue mulching did not significantly influence the water content at the permanent wilting point, regardless of tillage treatment (Figures 16 and 17).

The maximum available water for root extraction (AWmax), an analogous to the least limiting water range (LLWR) was not significantly ($p<0.05$) by tillage in all cases. Initially, the average values of AWmax in the 0-10 cm surface layer were at par, about 0.15 cm^3 cm^{-3}. At harvest of 2010/2011, 2011/2012 and 2012/2013 growing season, the average values of AWmax in the surface layer varied between 0.16 and 0.18 cm^3 cm^{-3}; 0.13 and 0.16 cm^3 cm^{-3} for; and from 0.14 to 0.16 cm^3 cm^{-3}, respectively, with none of the tillage methods having dominion over the other (Table 10).

For the deeper layers, initial average values of AWmax were between 0.14 and 0.17 cm^3 cm^{-3}. At harvest of 2010/2011 growing season, the average values of AWmax values in the deeper layers were between 0.16 and 0.18 cm^3 cm^{-3} were between. In subsequent growing seasons, the AWmax slightly reduced, with average AWmax values between 0.11 and 0.16 cm^3 cm^{-3} at harvest of 2011/2012 growing season and between 0.13 and 0.16 cm^3 cm^{-3} at the end of 2012/2013 growing season, respectively (Table 10).

Regardless of tillage method, residue mulching did not significantly ($p<0.05$) influenced AWmax (Table 10), with average profile AWmax values from mulched treatment at par with that of no mulch treatment in all the soil layers and for both growing seasons Table 10).

3. Soil organic matter, total nitrogen, carbon pool and C/N ratio

The results of average values and statistical analysis of total soil organic matter (SOM), total nitrogen (TN), soil organic carbon to nitrogen (C/N) ratio, and carbon pool (Cpool) are presented in Table 11. In the 0-10 cm surface layer, the effect of tillage treatment was significant ($p<0.05$) only on Cpool in 2011/2012 growing season.

Initially (2010), the average values of TN, SOM, C/N and Cpool were 0.67 g/kg; 1.3%; 11.2; and 12 Mg/ha, respectively. At the end of harvest in 2010/2011 growing season, average values of TN slightly decreased, ranging between 0.56 and 0.64 g/kg; average SOM content increased in untilled treatments (NT and NTC) and decreased in tilled treatments (Chi and CT). The treatments had increased C/N ratio, with values between 12 and 14 while average Cpool values were from 12 to 14 Mg/ha. In 2011/2012 season, the average concentration of TN of the 0-10 cm surface layer was between 0.46 g/kg and 0.61 g/kg, lower compared with the initial value. The average SOM values of this superficial layer ranged from 1.28 to 1.61% while the average values of C/N ratio from the different tillage methods

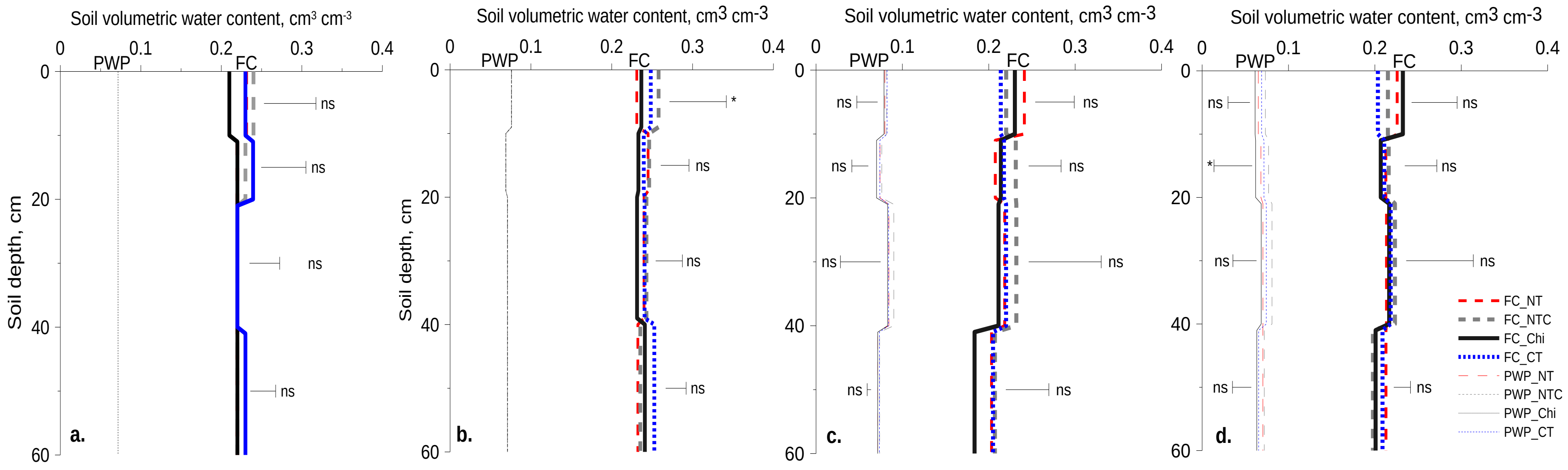


Figure 15. Field capacity (FC, cm^3 cm^{-3}) and permanent wilting point (PWP, cm^3 cm^{-3}) for the 0-10, 10-20, 20-40 and 40-60 cm soil layers of the sugarcane field under different tillage methods at (a) initial, 2010[§], (b) 2010/2011[§], (c) 2011/2012, and (d) 2012/2013 growing seasons at Santa Maria, southern Brazil.

NT: No-tillage; NTC: Compacted no-tillage; Chi: Chisel tillage; CT: Conventional tillage

Horizontal half-bars are the mean significant difference values at 5% level of probability by LSD-test; *significant; ns: not significant

[§] data collected by Fontanela (2012).

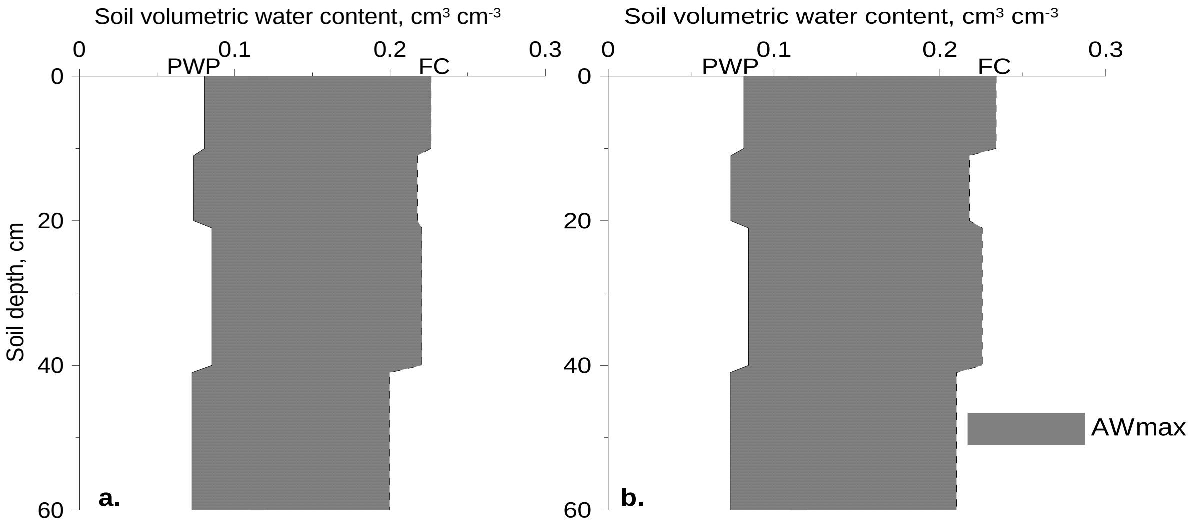


Figure 16. Field capacity (FC, cm^3 cm^{-3}); permanent wilting point (PWP, cm^3 cm^{-3}) and maximum available water content (AWmax, cm^3 cm^{-3}) for the 0-10, 10-20, 20-40 and 40-60 cm soil layers of the sugarcane field under (a) no mulching and (b) residue mulching during 2011/2012 growing season at Santa Maria, southern Brazil.

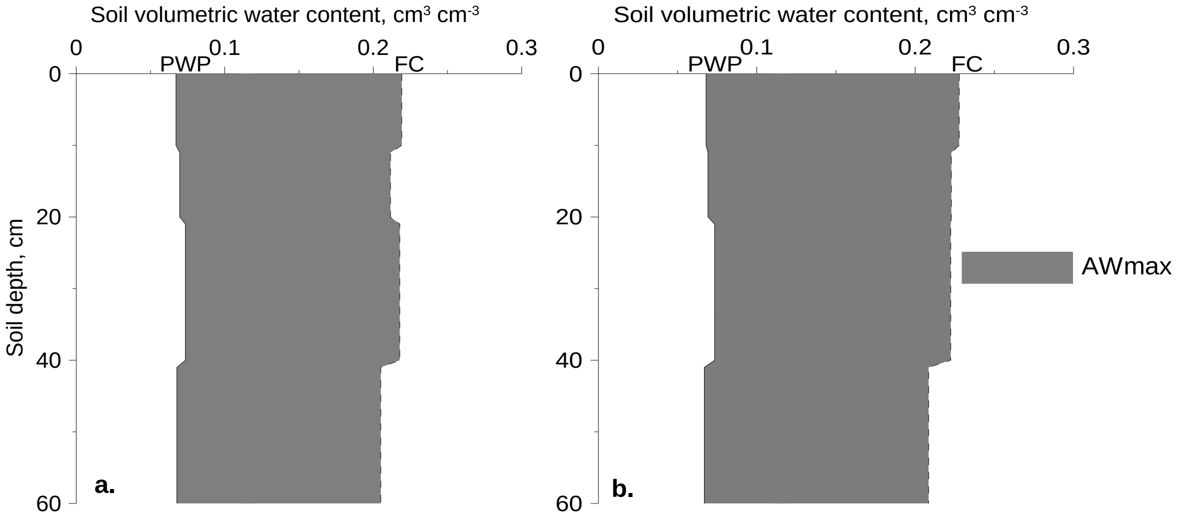


Figure 17. Field capacity (FC, cm^3 cm^{-3}); permanent wilting point (PWP, cm^3 cm^{-3}) and maximum available water content (AWmax, cm^3 cm^{-3}) for the 0-10, 10-20, 20-40 and 40-60 cm soil layers of the sugarcane field under (a) no mulching and (b) residue mulching during 2012/2013 growing season at Santa Maria, southern Brazil.

increased, with values between 13.0 and 17.0 and those of Cpool ranged from 11.3 to 15.0 Mg/ha. At the end of 2012/2013 growing season, the average TN values of the 0-10 cm layer reduced further, with values between 0.46 to 0.63 g/kg. Likewise, the average values of SOM for this layer ranged between 1.28 and 1.53%, with increase in NT treatment and no change in CT treatment. With further decrease in TN, the average C/N ratio increased, with values ranging between 14.1 and 16.1 while the average values of Cpool generally remained unchanged (Table 11).

Regardless of tillage method, a comparison of the SOM between residue mulching and no mulching at harvest of 2011/2012 growing season showed that the average SOM of the 0-10 cm surface layer of the sugarcane field was slightly higher in residue mulch treatment (0.60%) than no mulch treatment (0.55%), however the difference was not significant. Similar non-significant differences were obtained for other variables (TN, C/N and Cpool). At harvest of 2012/2013 growing season and for this surface layer, no significant differences were obtained for all the variables (Table 11).

For the 10-20 and 20-40 cm subsurface soil layers, the average values of TN, SOM and Cpool decreased while the C/N ratio increased with soil depth and over season, however these differences were not significant ($p<0.05$). Similar to previous results, no significant interaction between tillage methods and residue mulching was observed for these variables in all cases (Table 11).

Table 11. Average values of total nitrogen (TN) and soil organic matter (SOM), carbon/nitrogen ratio (C/N), and soil organic carbon pool (Cpool) for the 0-10, 10-20 and 20-40 cm soil layers of the sugarcane field under different tillage methods and residue mulching at initial in 2010 and at harvest of 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, southern Brazil.

	2010 (Initial)§				2010/2011§				2011/2012				2012/2013			
	TN	SOM	C/N	Cpool	TN	SOM	C/N	Cpool	TN	SOM	C/N	Cpool	TN	SOM	C/N	Cpool
Treatments	g/kg	%		Mg/ha	g/kg	%		Mg/ha	g/kg	%		Mg/ha	g/kg	%		Mg/ha
	0-10 cm soil layer															
NT	0.67	1.3	11.2	12.4	0.64	1.36	12.2	12.5	0.61	1.41	13.4	12.5	0.63	1.53	14.1	12.7
NTC	0.67	1.3	11.2	12.4	0.61	1.46	14.2	13.8	0.55	1.61	17.0	15.0	0.55	1.44	15.2	13.2
Chi	0.67	1.3	11.2	11.4	0.56	1.29	13.3	12.8	0.46	1.28	16.1	11.3	0.57	1.45	14.8	12.2
CT	0.67	1.3	11.2	12.0	0.62	1.29	12.1	12.0	0.57	1.28	13.0	11.7	0.46	1.28	16.1	10.9
NM	-	-	-	-	-	-	-	-	0.55	1.40	14.7	12.6	0.55	1.42	15.0	12.2
M	-	-	-	-	-	-	-	-	0.60	1.47	14.2	12.9	0.59	1.50	14.7	12.4
T	-	-	-	-	0.34^{ns}	0.75^{ns}	1.38^{ns}	0.87^{ns}	1.91^{ns}	2.58^{ns}	2.38^{ns}	3.27*	0.40^{ns}	0.62^{ns}	1.22^{ns}	1.50^{ns}
M$_e$	-	-	-	-	-	-	-	-	2.18^{ns}	0.02^{ns}	0.12^{ns}	0.14^{ns}	0.00^{ns}	0.00^{ns}	0.00^{ns}	0.04^{ns}
T x M	-	-	-	-	-	-	-	-	2.52^{ns}	2.88^{ns}	2.67^{ns}	2.35^{ns}	0.90^{ns}	0.83^{ns}	0.74^{ns}	0.78^{ns}
	10-20 cm soil layer															
NT	0.51	1.0	11.5	9.9	0.49	1.02	10.9	9.7	0.53	1.03	15.5	10.0	0.32	1.00	18.1	9.7
NTC	0.51	1.0	11.5	10.0	0.58	0.99	11.4	9.4	0.65	0.97	18.7	9.7	0.23	0.92	23.2	9.6
Chi	0.51	1.0	11.5	9.8	0.36	0.92	14.9	8.6	0.22	0.83	21.9	7.6	0.30	1.00	19.3	9.1
CT	0.51	1.0	11.5	10.1	0.41	1.05	14.8	9.9	0.32	1.09	19.8	10.6	0.27	0.97	19.4	9.5
NM	-	-	-	-	-	-	-	-	0.57	0.98	12.5	9.5	0.29	0.97	20.7	9.5
M	-	-	-	-	-	-	-	-	0.47	1.01	15.8	9.9	0.31	0.99	18.5	9.6
T	-	-	-	-	0.79^{ns}	1.07^{ns}	0.95^{ns}	1.36^{ns}	0.60^{ns}	2.88^{ns}	1.21^{ns}	1.70^{ns}	0.73^{ns}	1.02^{ns}	1.21^{ns}	0.40^{ns}
M$_e$	-	-	-	-	-	-	-	-	0.00^{ns}	0.72^{ns}	0.00^{ns}	0.43^{ns}	0.15^{ns}	0.59^{ns}	0.46^{ns}	0.08^{ns}
T x M	-	-	-	-	-	-	-	-	0.80^{ns}	1.69^{ns}	0.75^{ns}	1.61^{ns}	0.32^{ns}	0.70^{ns}	1.95^{ns}	0.57^{ns}

Table 11 contd.

Treatments	TN g/kg	SOM %	C/N	Cpool Mg/ha	TN g/kg	SOM %	C/N	Cpool Mg/ha	TN g/kg	SOM %	C/N	Cpool Mg/ha	TN g/kg	SOM %	C/N	Cpool Mg/ha
	20-40 cm soil layer															
NT	0.46	0.97	12.2	18.5	0.35	0.94	15.5	18.1	0.24	0.91	22.0	17.6	0.22	0.90	24.7	23.7
NTC	0.46	0.97	12.2	19.6	0.33	0.93	16.2	18.4	0.21	0.87	24.0	18.4	0.21	0.94	27.1	26.0
Chi	0.46	0.97	12.2	19.5	0.32	0.90	16.4	16.6	0.18	0.83	26.7	15.9	0.21	0.93	27.0	25.7
CT	0.46	0.97	12.2	19.9	0.32	0.91	16.3	17.5	0.19	0.85	25.9	16.4	0.21	0.93	25.7	25.7
NM	-	-	-	-	-	-	-	-	0.20	0.87	25.2	17.1	0.21	0.87	26.3	24.0
M	-	-	-	-	-	-	-	-	0.21	0.85	23.4	17.3	0.22	0.87	26.1	25.6
T	-	-	-	-	0.92^{ns}	0.23^{ns}	0.32^{ns}	1.02^{ns}	16.94^{ns}	1.21^{ns}	9.01^{ns}	1.19^{ns}	0.30^{ns}	0.55^{ns}	0.80^{ns}	0.23^{ns}
M_e	-	-	-	-	-	-	-	-	23.73^{ns}	3.61^{ns}	5.90^{ns}	4.24^{ns}	0.15^{ns}	0.59^{ns}	0.46^{ns}	0.08^{ns}
T x M	-	-	-	-	-	-	-	-	6.55^{ns}	0.43^{ns}	2.25^{ns}	0.58^{ns}	0.38^{ns}	0.46^{ns}	0.51^{ns}	0.33^{ns}

NT: no-tillage; NTC: compacted no-tillage; Chi: chisel tillage; CT: conventional tillage; NM: no mulching; M: residue mulching; T: tillage effect; M_e: mulching effect; T x M: tillage x mulching interaction

*significant; ns: not significant.at 5% level of probability by Fisher’s Least significant difference (LSD).

§data collected by Fontanela (2012).

4. Pre-compression stress and compression index

The statistical results and seasonal distribution of pre-compression stress, σ_c, and compression index, I_c, for the 0-10, 10-20 and 20-40 cm soil layers of the sugarcane field under different tillage methods at the beginning (2010) and end of 2010/2011, 2011/2012, and 2012/2013 growing seasons are presented in Table 12 and Figures 18 and 19. Figures 20 and 21 show the effect of residue mulching treatment on both σ_c and I_c.

The σ_c was not statistically significant ($p<0.05$) under tillage treatments in all the soil layers shortly after tillage and at the end of the three consecutive growing seasons. Initially, average values of σ_c were between 88.2 and 108.0 kPa. At harvest of 2010/2011 growing season, the 0-10 cm surface layer had average values of σ_c ranging between 92.8 and 117.3 kPa. In 2011/2012 growing season, the average values of σ_c were between 127.0 and 192.2 kPa while at the end of 2012/2013 growing season, the average values of σ_c in this surface layer ranged between 175.9 and 289.7 kPa, with the values higher in subsequent growing season compared with previous season (Figure 18).

For the 10-20 cm layer, the average initial values of σ_c were between 71.7 and 118.5 kPa; and for subsequent growing seasons, the values were between 88.3 and 124.2 kPa; 152.8 and 312.3 kPa; and 243.8 and 354.4 kPa for the 2010/2011, 2011/2012, and 2012/2013, respectively. Also in this layer, none of the tillage treatments dominate considering ranking of values of σ_c (Figure 18).

For the 20-40 cm deeper layer, the σ_c had highest average value in NTC treatment (106.7 kPa) while those of other treatments were at par shortly after tillage treatment. At the end of 2010/2011 growing season, the average values σ_c were at par while at harvest of 2011/2012 and 2012/2013 seasons, similar differences in values σ_c were observed (Figure 18).

A comparison of the seasonal variability of σ_c showed that the soil mechanical property increased with season in all layers, with the seasonal trend as initial (2010) <2010/2011<2011/2013<2012/2013 (Figure 18).

Irrespective of tillage treatments, residue mulching did not significantly ($p<0.05$) influence σ_c in both 2011/2012 and 2012/2013 growing seasons (Figure 20). The interaction between tillage and residue mulching was not significant on the pre-compression stress of all the soil layers evaluated in this study (Table 12).

Table 12. Statistical comparison of the pre-compression stress, σ_c, and compression index, I_c, of the 0-10, 10-20 and 20-40 cm soil layers of the sugarcane field under different tillage methods and residue mulching at initial (2010) and end of 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, southern Brazil.

Statistical parameters	2010 (Initial)		2010/2011		2011/2012		2012/2013	
	σ_c, kPa	I_c	σ_c, kPa	I_c	σ_c, kPa	I_c	σ_c, kPa	I_c
	0-10 cm soil layer							
T	1.25^{ns}	0.52^{ns}	0.43^{ns}	0.65^{ns}	0.02^{ns}	1.29^{ns}	1.24^{ns}	0.50^{ns}
M_e	-	-	-	-	0.49^{ns}	0.75^{ns}	0.44^{ns}	0.04^{ns}
T x M	-	-	-	-	0.77^{ns}	1.07^{ns}	0.17^{ns}	0.01^{ns}
	10-20 cm soil layer							
T	0.68^{ns}	0.97^{ns}	0.26^{ns}	1.54*	0.07^{ns}	0.71^{ns}	1.09^{ns}	3.79*
M_e	-	-	-	-	0.01^{ns}	1.32^{ns}	0.46^{ns}	2.08^{ns}
T x M	-	-	-	-	0.75^{ns}	0.11^{ns}	1.87^{ns}	0.70^{ns}
	20-40 cm soil layer							
T	1.87^{ns}	0.49^{ns}	0.67^{ns}	0.34^{ns}	0.51^{ns}	0.49^{ns}	0.10^{ns}	3.75*
M_e	-	-	-	-	1.66^{ns}	0.40^{ns}	0.24^{ns}	0.06^{ns}
T x M	-	-	-	-	0.11^{ns}	0.57^{ns}	1.13^{ns}	0.16^{ns}

T: tillage effect; M_e: mulching effect; T x M: tillage x mulching interaction

*significant at 5% probability level by Fisher's LSD-test; ^{ns}: not significant.

The compression index, I_c, in the 0-10 cm surface layer was not significantly ($p<0.05$) affected by tillage treatments shortly after soil mobilization and at the end of each growing season, however, the effect of tillage on I_c was significant in the 10-20 cm layer in both 2010/2011 and 2012/2013 growing seasons and only in the 20-40 cm layer in 2012/2013 season (Table 12). The average values of I_c decreased with soil depth, with the average I_c values in the surface layer almost or more than twice those obtained in the 40-60 cm subsurface layer (Figure 19). The initial average values of I_c were between 0.10 and 0.24; and subsequently between 0.09 and 0.19; 0.13 and 0.27; and 0.08 and 0.23 at the end of 2010/2011, 2011/2012 and 2012/2013 growing seasons, respectively. The opposite result was obtained in terms of seasonal changes of I_c, with the trend as 2010>2010/2011>2011/2012>2012/2013.

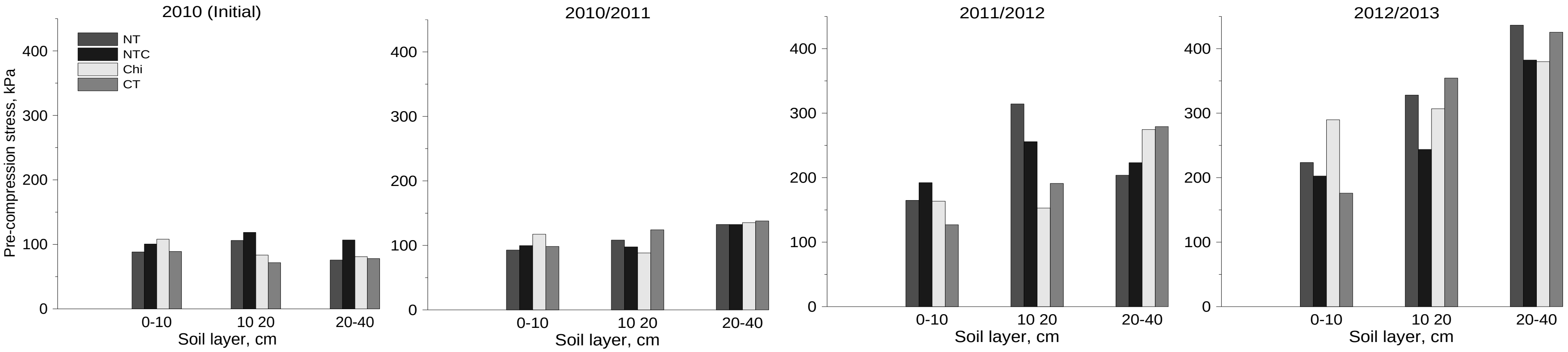


Figure 18. Seasonal distribution of pre-compression stress, σ_c, for the 0-10, 10-20 and 20-40 cm soil layers of the sugarcane field under different tillage methods at initial and at harvest of three consecutive growing seasons at Santa Maria, southern Brazil.

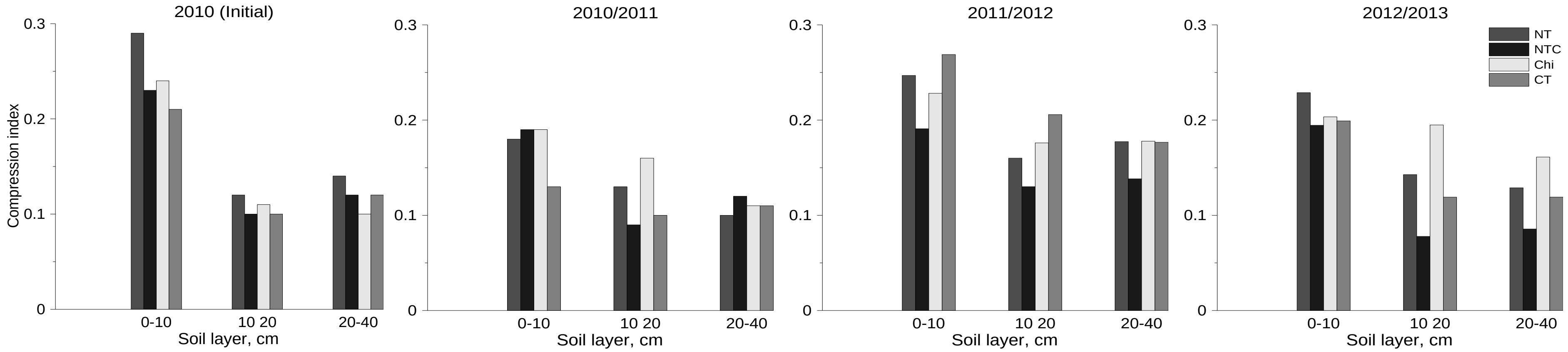


Figure 19. Seasonal distribution of compression index, I_c, for the 0-10, 10-20 and 20-40 cm soil layers of the sugarcane field under different tillage methods during the 2010/2011, 2011/2012, and 2012/2013 growing seasons at Santa Maria, southern Brazil.

NT: No-tillage; NTC: Compacted no-tillage; Chi: Chisel tillage; CT: Conventional tillage

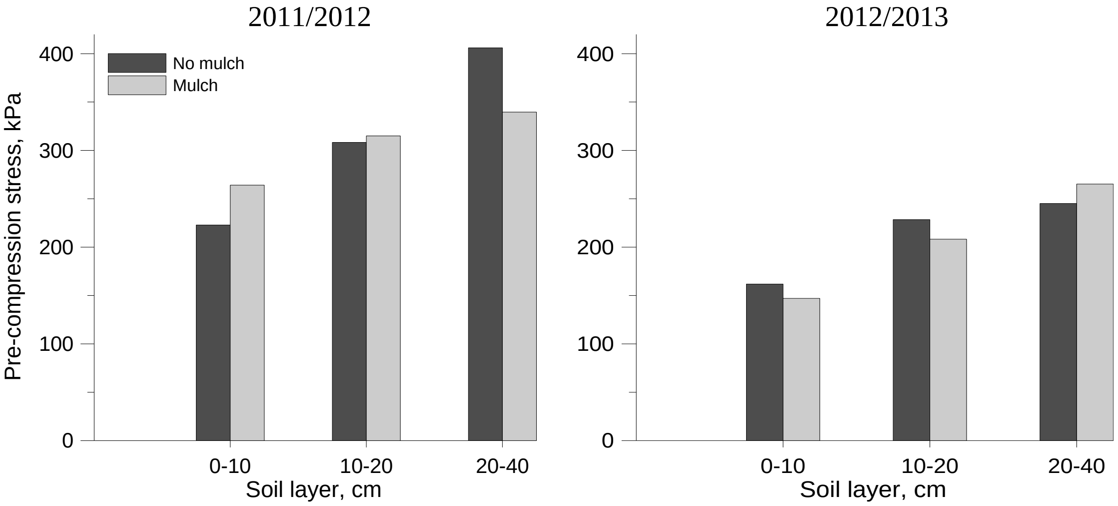


Figure 20. Pre-compression stress, σ_c (kPa) for the soil layers, 0-10, 10-20 and 20-40 cm of the sugarcane field under residue mulch and no mulching during 2011/2012 and 2012/2013 growing seasons at Santa Maria, southern Brazil.

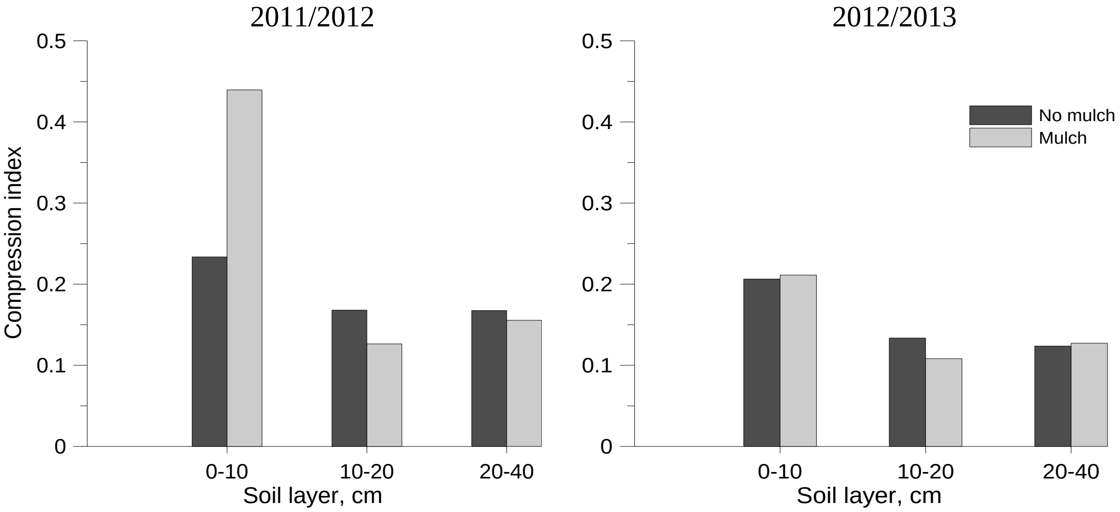


Figure 21. Compression index, I_c, of the soil layers, 0-10, 10-20 and 20-40 cm of the sugarcane field under residue mulch and no mulching during 2011/2012 and 2012/2013 growing seasons at Santa Maria, southern Brazil.

Residue mulching also had no significant effect ($p<0.05$) on compression index. The average values of I_c was higher in the mulched surface layer (0.44) compared with no mulch surface layer (0.23) in 2011/2012 growing season, while the values were at par (0.21) in 2012/2013 growing season. In 10-20 cm soil layer, the average values of I_c were higher in no mulched treatment than mulched treatment in both 2011/2012 and 2012/2013 growing seasons. For the 20-40 cm layer, the average value of I_c was higher in no mulch treatment compared with mulched treatment in 2011/2012 season, however opposite result was observed in 2012/2013 season (Figure 21). Likewise, the interaction between tillage and residue mulching was not significant ($p<0.05$) on the average values of the compression index of the different soil layers evaluated (Table 12).

5. Degree of compaction

The seasonal distribution of the average values of degree of compaction (DC) of the different soil layers and treatments are presented in Table 13. Shortly after tillage in 2010, the average values of DC of the 0-10 cm surface layer varied between 83 and 90%, with significantly highest value from NTC treatment. At harvest of 2010/2011 growing season, average DC values of this surface layer were between 87 and 93%, however the values did not differ from one another. Comparing with previous values, no discernible difference was observed. For the 2011/2012 growing season, the DC values ranged from 83 to 90%, which did not significantly differ among the different tillage methods. Similarly, the average values of DC did not change compared with previous values. At the end of 2013/2013 growing season, the average values of DC of the 0-10 cm layer ranged between 79 and 87%, with no significant difference among the tillage treatments. Unlike previous seasons, the DC decreased (Table 13).

For the 10-20 and 20-40 cm layers, higher average values of DC were obtained, at initial and end of the seasons. The average DC values were not less than 90% (as high as 97% from CT treatment, though not significantly difference from other treatments).

Irrespective of tillage methods, residue mulching did not significantly ($p<0.05$) affect DC, however lower values of DC were obtained from the 0-10 cm surface layer of mulched treatment during the two years of application (Table 13).

Table 13. Average values and statistical comparison of degree of compaction, DC (%) of the 0-10, 10-20 and 20-40 cm layers of the sugarcane field at initial (2010) and at harvest of 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, Brazil.

	----------------------------------Treatments--------------------------------						-----Effect----	
Soil	NT	NTC	Chi	CT	M	NM	T	M_e
depth, cm	2010 (Initial)							
0-10	89	90	83	83	-	-	9.77*	-
10-20	92	94	92	95	-	-	1.35^{ns}	-
20-40	90	95	94	96	-	-	3.37^{ns}	-
	2010/2011 growing season							
0-10	86	89	92	87	-	-	1.61^{ns}	-
10-20	89	89	88	88	-	-	0.08^{ns}	-
20-40	90	92	86	90	-	-	1.45^{ns}	-
	2011/2012 growing season							
0-10	87	90	83	84	85	86	0.18^{ns}	1.13^{ns}
10-20	91	94	90	91	91	92	1.21^{ns}	2.10^{ns}
20-40	92	96	90	95	92	93	3.58^{ns}	0.99^{ns}
	2012/2013 growing season							
0-10	79	87	81	80	81	84	2.13^{ns}	1.22^{ns}
10-20	92	96	90.	94	92	93	3.24^{ns}	1.02^{ns}
20-40	93	97	91	93	93	93	1.04^{ns}	0.07^{ns}

NT: no-tillage; NTC: compacted no-tillage; Chi: chiseling tillage; CT: conventional tillage; M: residue mulching; NM: no mulching; T: tillage effect; M_e: mulching effect.
ns: not significant at 5% level of probability by Fisher's Least square difference (LSD)

4.1.3 Soil water retention (SWR)

The average soil water retention (mm) in the 0-10, 10-20 and 20-40 cm layers and total soil profile water retention (mm) of the sugarcane field and the statistical comparison during 2010/2011, 2011/2012 and 2012/2013 growing seasons are presented in Table 14. In 2010/2011 growing season, the average values of soil water retention (SWR) did not significantly ($p<0.05$) differ among the tillage methods for all the soil layers and overall soil profile. For the 0-10 cm surface layer, the average value of SQI was almost at par (about 18

Table 14. Average soil water retention (mm) in the 0-10, 10-20 and 20-40 cm layers and total soil profile water retention (mm) of the sugarcane field, with the statistical comparison during 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, Brazil.

	---------------Soil depth, cm-------------			
	0-10	10 20	20-40	Total
Treatment	2010/2011 growing season			
NT	18	21	40	79
NTC	18	21	41	80
Chi	19	21	40	79
CT	18	18	42	77
LSD (*p<0.05*)				
T	0.33^{ns}	2.57^{ns}	0.39^{ns}	0.27^{ns}
	2011/2012 growing season			
NT	24	25	50	100
NTC	25	26	51	102
Chi	23	25	49	97
CT	23	24	51	98
NM	25	26	52	103
M	24	25	50	99
LSD (*p<0.05*)				
T	0.36^{ns}	1.53^{ns}	1.63^{ns}	1.43^{ns}
M_e	0.54^{ns}	2.24^{ns}	3.20^{ns}	16.43^{ns}
T x M	0.83^{ns}	1.28^{ns}	0.02^{ns}	0.37^{ns}
	2012/2013 growing season			
NT	24	26	50	100
NTC	25	27	53	105
Chi	24	25	52	101
CT	24	26	54	104
NM	26	27	54	107
M	24	26	52	102
LSD (*p<0.05*)				
T	0.41^{ns}	1.11^{ns}	1.53ns	1.51^{ns}
M_e	2.42^{ns}	3.18^{ns}	3.15^{ns}	1.35^{ns}
T x M	0.98^{ns}	0.38^{ns}	3.54^{ns}	1.33^{ns}

NT: no-tillage; NTC: compacted no-tillage; Chi: chiseling tillage; CT: conventional tillageM: residue mulching; NM: no mulching; T: tillage effect; M_e: mulching effect; T x M: tillage and mulching interaction

ns: not significant at 5% level of probability by Fisher’s Least square difference (LSD) mm), while it was about 20 and 40 mm for the 10-20 and 20-40 cm layers, respectively. The total soil profile water retention was about 80 mm.

For 2011/2012 growing season, there was no significant difference in the average values of SWR among the different tillage methods for all the soil layers as well as overall soil profile. The average values of SWR for the 0-10 cm surface layer was about 24 mm while for the 10-20 and 20-40 cm layers, the average values were about 25 and 50 mm, respectively and about 100 mm for the overall (0-40 cm) soil profile. Comparing with the results obtained for the previous season, the average values of SWR was higher by about 30, 23, 23 and 26% for the 0-10, 10-20, 20-40 and overall soil profile, respectively (Table 14).

Regardless of tillage treatment, the average soil water retention per layer and total soil profile water retention appeared to be higher in residue mulch treatment compared with no mulch treatment, however, the difference was not significant ($p<0.05$). Likewise, there was no significant interaction between tillage and residue mulching on the average and total soil profile water retention.

In 2012/2013 growing season, tillage effect was not significant ($p<0.05$) on average SWR in all the soil layers. The 0-10 cm superficial layer had average SWR values about 24 mm. In the 10-20 cm layer, average values of SWR were also at par (about 26 mm). For the 20-40 cm deeper layer, average value of SWR was about 50 mm). Likewise, the total soil profile water retention did not differ among the tillage methods, with average value around 102 mm (Table 14).

Similarly, the effect of residue mulching was not significant ($p<0.05$) on both average water retention per layer and total soil profile water retention, regardless of tillage method.

Also, tillage and residue mulching treatments did not have significant interaction on soil water retention. A comparison of the average SWR values (2012/2013 growing season) with those of the initial season (2010/2011) showed that SWR increased by about 33, 28, 28 and 30% for the 0-10, 10-20, 20-40 cm layers and overall soil profile, respectively. Similarly, the average SWR values obtained in this growing season did not differ from the previous season (2011/2012) (Table14).

Table 15. Average yield of sugarcane (ton/ha), and statistical comparison among the different management practices, during 2010/2011 and 2011/2012 growing seasons at Santa Maria, Brazil.

	Average sugarcane yield, ton/ha		
Treatments	2010/2011 growing season	2011/2012 growing season	Average
NT	113	103	108
NTC	100	92	96
Chi	102	110	106
CT	94	120	107
NM	-	106	
M	-	118	
LSD ($p<0.05$)			
T	0.65^{ns}	2.13^{ns}	
M	-	1.33^{ns}	
T x M	-	0.54^{ns}	

NT: no-tillage; NTC: compacted no-tillage; Chi: chiseling tillage; CT: conventional tillage; T: tillage effect; M: mulching effect; T x M: tillage and mulching interaction

ns: not significant at 5% level of probability by Fisher's Least square difference (LSD).

4.1.4 Sugarcane yield

The average yield of sugarcane and results of statistical comparison during 2010/2011and 2011/2012 growing seasons are presented in Table 15. Soil tillage did not significantly ($p<0.05$) influence sugarcane yield. In 2010/2011 growing season, the average values of sugarcane yield varied between 94 and 113 ton/ha, while in 2011/2012 growing season, the average sugarcane yield values ranged from 92 and 120 ton/ha. Likewise, sugarcane yield from residue mulch treatment (118 t/ha) did not significantly ($p<0.05$) differ from that of no mulch treatment (106 t/ha). Similarly, tillage and residue mulching had no significant ($p<0.05$) interaction on sugarcane yield (Table 15).

4.2 Soil quality indicators

1. Minimum data set (MDS)

The rotated factor loadings, communalities, eigenvalues, proportion of the total variance explained by each principal component (PC) and cumulative variance of the principal component factors of the 0-10, 10-20 and 20-40 cm soil layers of the sugarcane field at initial (October 2010) and after each of the 2010/2011, 2011/2012 and 2012/2013 growing seasons are presented in Tables 16, 17 and 18.

For the 0-10 cm superficial layer, four (4) PCs in 2010, five (5) PCs in 2011 and 2012 while three (3) PCs had eigenvalues greater than 1. The proportion of the total variance explained by each principal component ranged from 8.2 to 37.4%, and the PCs could only explain cumulative variance of 96.6, 96.4, 85.8 and 84.3% for the initial (2010), 2010/2011, 2011/2012 and 2012/2013 growing seasons, respectively (Table 16). For the 10-20 cm soil layer, four (4) PCs in 2010 and 2011, five (5) PCs in 2012 while three (3) PCs in 2013 had eigenvalues greater than 1. The proportion of variance explained was between 8.1 and 51.7%, with the initial and seasonal cumulative variance explained by the PCs was between 81.6 and 88.5% (Table 17).

For the 20-40 cm deeper layer, four (4) PCs had eigenvalues greater than 1 at initial and after each season. The proportion of the variance attributed to each PC ranged from 8.6 to 33.5%, and the initial and seasonal cumulative variance of all PCs was not more than about 87% (Table 18).

In 2010 (initial), the principal component analysis of the 0-10 cm layer had PC1 (Table 16) with TN, SOM and Cpool as variables with high loading rates, and was designated as organic matter and nutrient storage limiting group. TN was selected to represent nutrient cycling while SOM was retained as organic matter factor because of it higher loading rate and communality over Cpool. For PC2, BD, Pt and Ma had highest loading rates, and were designated as water retention and permeation group. BD was retained because it had highest correlation sum as well as highest loading rate and communality. PC3 had σ_c as the only variable with high loading rate and it was retained for further analysis. PC4 had FC and AW

Table 16. Rotated factor loadings and communalities of the management soil quality indicators of the 0-10 cm surface layer of the sugarcane field at initial (October 2010) and after each of the 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, Brazil.

	2010					2010/2011						2011/2012						2012/2013			
Soil	---------------PC---------------					-------------------------PC---------------------						----------------------------PC--------------------						-------------PC---------			
Par.	1	2	3	4	Com	1	2	3	4	5	Com	1	2	3	4	5	Com	1	2	3	Com
BD	-.13	**-.97***	-.13	-.04	.99	**-.95**	-.20	-.04	.07	-.06	.95	**-.91**	.10	-.20	.15	.13	.92	**-.96**	-.09	-.05	.93
Pt	-.27	**.92**	.02	-.10	.93	**.88**	.43	.01	.17	.01	.99	**.89**	-.09	.32	-.02	-.25	.97	**.95**	.15	.07	.92
Ma	.20	**.97**	-.04	.05	.98	**.96**	.00	-.04	.20	.04	.97	**.93**	-.08	.05	-.13	.27	.96	**.90**	.01	-.39	.96
Mi	-.23	-.15	.91	-.06	.91	.25	**.96**	.10	.02	-.06	.99	.02	-.02	.43	.16	-.77	.79	-.01	.27	**.93**	.94
FC	-.14	-.09	-.05	**.97**	.96	.07	**.99**	.06	.07	-.06	.99	.22	.12	**.91**	-.18	.13	.93	-.06	.27	**.93**	.94
PWP	.21	.18	.84	-.18	.82	.13	-.21	.03	-.22	**.92**	.95	-.03	.20	.12	-.07	**.75**	.63	-.40	.31	-.44	.45
AW	-.13	-.09	-.05	**.97**	.96	.07	**.98**	.07	.07	-.07	.99	.24	.02	**.88**	-.15	-.24	.91	.10	.13	**.98**	.99
TN	**.98**	.14	.04	-.03	.99	.63	.03	**.65**	-.23	-.35	.99	.12	.43	.30	**-.77**	.25	.95	.19	**.95**	.21	.98
SOM	**.95**	.14	-.17	.00	.96	.20	.18	**.95**	.02	.06	.98	-.01	**.92**	.21	.00	.24	.95	.23	**.94**	.08	.95
C/N	-.76	-.02	-.49	.09	.83	-.62	.19	.13	.39	.59	.94	-.17	.07	-.12	**.96**	-.06	.97	-.08	-.78	-.34	.73
Cpool	**.92**	-.21	-.24	-.02	.95	-.20	.11	**.96**	.05	.06	.99	-.35	**.86**	.12	.06	.27	.96	-.21	**.95**	.05	.94
σ_c	-.10	.07	**.83**	.15	.72	-.16	-.14	-.08	**-.93**	.14	.94	.10	**.57**	-.20	-.28	-.35	.58	**-.71**	.10	-.09	.52
I_C	-.37	-.32	-.08	-.73	.78	-.10	-.12	.73	**.56**	.04	.88	.34	**-.51**	.38	.33	.05	.63	**.81**	.19	.13	.70
Eigen	3.9	3.0	2.6	2.3		4.58	2.96	2.42	1.31	1.27		3.9	3.1	1.7	1.3	1.1		4.9	3.8	2.3	
Var,. %	29.9	23.0	20.2	17.5		35.2	22.7	18.6	10.1	9.8		30.6	24.1	13.0	9.9	8.2		37.4	29.2	17.7	
Cum, %	29.9	52.9	73.1	90.6		35.2	57.9	76.5	86.6	96.4		30.6	54.7	67.7	77.6	85.8		37.4	66.6	84.3	

Soil Par: soil parameter; PC: principal component; Com: communality; SOM: soil organic matter, %; Cpool: soil organic carbon density, Mg/ha; TN: total nitrogen, g/kg; C/N: carbon to nitrogen ratio; BD: bulk density, g/cm^3; Pt: total porosity, cm^3 cm^{-3}; Ma: macroporosity, cm^3 cm^{-3}; Mi: microporosity, cm^3 cm^{-3}; FC: field capacity, cm^3 cm^{-3}; PWP: permanent wilting point, cm^3 cm^{-3}; AW: available water capacity, mm; σ_c: pre-compression stress, kPa; I_c: compression index.

Eigen: eigenvalues; Var.: variance explained by each parameter, %; Cum: cumulative variance explained.

*Values in bold in each PC column were used to select the minimum data set (MDS)

Table 17. Rotated factor loadings and communalities of the management soil quality indicators of the 10-20 cm layer of the sugarcane field at initial (October 2010) and after each of the 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, Brazil.

Soil	2010					2010/2011					2011/2012						2012/2013			
	PC					PC					PC						PC			
Par.	1	2	3	4	Com	1	2	3	4	Com	1	2	3	4	5	Com	1	2	3	Com
BD	.64	.08	**-.94***	-.12	.73	-.11	**-.93**	-.01	-.23	.94	**.87**	-.05	-.23	.11	-.14	.84	-.15	**-.89**	.31	.90
Pt	-.02	-.12	.35	.87	.90	.34	**.92**	-.12	.11	.99	**-.89**	-.02	.12	-.20	.09	.85	.37	**.80**	-.23	.83
Ma	-.25	-.02	**.90**	.03	.87	-.03	**.97**	-.13	.13	.97	**-.82**	.00	.17	.11	.17	.74	-.01	**.89**	-.26	.87
Mi	.71	-.15	-.46	-.42	.92	**.98**	.17	-.02	-.01	.98	.02	.48	.07	.56	.00	.55	**.93**	.02	.00	.87
FC	-.13	**.96**	-.03	.06	.95	**.99**	.03	.04	-.09	.99	-.15	-.02	**.93**	.32	-.04	.98	**.96**	-.07	.03	.92
PWP	-.06	-.09	-.60	-.18	.40	.00	.17	.05	.40	.91	-.03	-.03	.27	**.86**	.05	.82	.15	-.22	.87	.82
AW	-.10	**.96**	-.04	.08	.95	**.98**	.04	.06	-.09	.98	-.16	-.01	**.95**	.05	-.07	.94	**.87**	.05	-.43	.94
TN	**.94**	-.16	-.03	-.16	.94	.09	-.15	**.84**	-.41	.91	.25	**.92**	-.02	-.08	-.01	.92	**.76**	.59	-.07	.93
SOM	**.95**	-.03	-.06	-.02	.91	-.06	.20	**.86**	.32	.89	.64	**.94**	.16	-.35	.24	.81	**.72**	.59	-.06	.87
C/N	-.21	.55	-.02	.63	.74	-.19	.17	**-.78**	.40	.83	.04	**-.91**	.04	-.09	.06	.83	-.60	-.50	.10	.62
Cpool	**.96**	-.01	-.12	-.03	.95	-.11	-.19	**.90**	.20	.89	**.87**	.32	.03	-.25	.14	.94	**.80**	.27	.08	.72
σ_c	.14	.38	.40	**-.89**	.87	.29	-.42	.04	**-.82**	.85	.06	.34	-.09	-.47	**-.86**	.86	-.21	-.25	**.60**	.87
I_C	.69	-.16	.43	**.76**	.71	-.35	.49	-.50	**-.79**	.70	-.12	.05	-.13	-.03	**.87**	.79	.06	**.91**	**-.08**	.84
Eigen	4.9	2.6	2.1	1.2		4.1	3.5	2.6	1.3		4.2	2.3	1.8	1.3	1.1		6.73	2.83	1.05	
Var,. %	37.7	20.2	16.3	9.2		31.8	26.8	20.1	9.9		32.1	17.6	14.1	10.1	8.3		51.7	21.8	8.1	
Cum, %	37.7	57.9	74.2	83.4		31.8	58.6	78.7	88.5		32.1	49.7	63.8	73.9	82.2		51.7	73.5	81.6	

Soil Par: soil parameter; PC: principal component; Com: communality; SOM: soil organic matter, %; Cpool: soil organic carbon density, Mg/ha; TN: total nitrogen, g/kg; C/N: carbon to nitrogen ratio; BD: bulk density, g/cm^3; Pt: total porosity, cm^3 cm^{-3};Ma: macroporosity, cm^3 cm^{-3}; Mi: microporosity, cm^3 cm^{-3}; FC: field capacity, cm^3 cm^{-3}; PWP: permanent wilting point, cm^3 cm^{-3}; AW: available water capacity, mm; σ_c: pre-compression stress, kPa; I_c: compression index. Eigen: eigenvalues; Var.: variance explained by each parameter, %; Cum: cumulative variance explained.*Values in bold in each PC column were used to select the minimum data set (MDS).

Table 18. Rotated factor loadings and communalities of the management soil quality indicators of the 20-40 cm subsurface layer of the sugarcane field at initial (October 2010) and after each of the 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, Brazil.

	2010					2010/2011					2011/2012					2012/2013				
Soil	-----------------PC-----------------					-----------------------PC----------------					---------------------PC-----------------					-------------------PC------------------				
Par.	1	2	3	4	Com	1	2	3	4	Com	1	2	3	4	Com	1	2	3	4	Com
BD	**-.92***	.11	.20	.17	.93	**-.95**	.19	.19	-.05	.97	.00	**.86**	.23	.06	.80	-.03	**-.85**	.28	-.05	.81
Pt	**.95**	-.10	-.14	-.12	.95	**.97**	-.08	-.12	.03	.97	.00	**-.96**	.06	-.01	.92	.12	**.82**	.48	-.15	.94
Ma	**.92**	-.07	.01	.24	.91	**.90**	-.40	-.06	.01	.98	-.03	**-.89**	-.37	-.05	.93	-.02	**.95**	-.13	-.03	.92
Mi	.31	.10	-.01	.40	.26	-.12	**.98**	-.14	.06	.99	.05	.04	**.85**	.08	.74	.21	-.08	**.93**	-.19	.96
FC	-.09	-.11	**.95**	.22	.97	-.18	**.96**	-.10	.13	.99	.11	.46	**.79**	.26	.92	.17	-.28	**.92**	-.16	.98
PWP	-.22	-.04	-.05	.77	.64	.15	.16	-.57	.09	.38	-.34	.20	.57	.10	.48	.03	-.39	.27	**-.80**	.87
AW	-.08	-.11	**.95**	.22	.97	-.20	**.96**	-.10	.13	.99	.35	.45	.64	.27	.81	.13	.13	.65	**.67**	.92
TN	-.18	**.87**	.10	.25	.85	-.01	.19	**.88**	**.93**	.93	**.93**	.05	-.28	-.06	.94	**.95**	.10	.14	.10	.94
SOM	.10	**.96**	-.16	-.19	.99	.14	-.06	**.90**	.33	.94	**.88**	-.13	.32	-.17	.92	**.94**	.15	.02	-.04	.91
C/N	.37	.43	-.34	-.57	.76	.12	-.23	.50	-.74	.88	-.72	-.12	.45	-.16	.75	**-.82**	.06	-.18	-.19	.74
Cpool	-.19	**.97**	-.10	-.13	1.00	-.45	.09	**.82**	.24	.94	**.87**	.09	.38	-.16	.92	**.93**	-.09	.12	-.05	.89
σ_c	-.22	.06	.75	**-.86**	.82	.43	.24	-.54	**.89**	.86	-.18	.05	.11	**.88**	.86	.11	-.22	-.11	**.65**	.65
I_C	.16	-.06	.42	**.76**	.78	-.17	.01	-.17	**-.86**	.80	-.01	-.04	-.14	**-.87**	.79	.03	.64	-.14	**.45**	.63
Eigen	3.9	3.3	2.0	1.7		4.4	3.3	2.5	1.1		4.3	3.2	1.7	1.3		4.0	3.4	2.0	1.6	
Var,. %	29.9	25.3	15.2	12.9		33.5	25.6	19.4	8.6		33.4	24.6	13.1	10.1		31.0	26.4	15.3	12.0	
Cum, %	29.9	55.3	70.5	83.4		33.5	59.2	78.5	87.1		33.4	58.0	71.1	81.3		31.0	57.5	72.7	84.7	

Soil Par: soil parameter; PC: principal component; Com: communality; SOM: soil organic matter, %; Cpool: soil organic carbon density, Mg/ha; TN: total nitrogen, g/kg; C/N: carbon to nitrogen ratio; BD: bulk density, g/cm^3; Pt: total porosity, cm^3 cm^{-3}; Ma: macroporosity, cm^3 cm^{-3}; Mi: microporosity, cm^3 cm^{-3}; FC: field capacity, cm^3 cm^{-3}; PWP: permanent wilting point, cm^3 cm^{-3}; AW: available water capacity, mm; σ_c: pre-compression stress, kPa; I_c: compression index.

Eigen: eigenvalues; Var.: variance explained by each parameter, %; Cum: cumulative variance explained.

*Values in bold in each PC column were used to select the minimum data set (MDS).

as variables with high loading rates. FC was retained to represent water retention (higher loading rate and communality than AW), Thus, TN, SOM, FC, BD and σ_c were retained as MDS for the 0-10 cm surface layer for 2010.

For the 2010/2011 growing season, PC1 had BD, Pt and Ma with highest loading rates, BD was retained because of highest loading rate and correlation sum. PC2 had FC, Mi and AW as variables with high loading rates, FC was retained because of highest loading rate and communality PC3 had both TN and SOM as variables with high loading rates, TN was selected to represent nutrient storage factor while SOM was selected as organic matter factor. PC4 had σ_c and I_c, however, σ_c was selected because of its higher loading rate and communality. Thus, the MDS for the 0-10 cm soil layer for 2010/2011 growing season were FC, BD, TN, SOM and σ_c.

For the 2011/2012 growing season, PC1 had BD, Pt and Ma as variables with high loading rates, BD was retained because of its highest loading rate. PC2 had OM, Cpool, σ_c and I_c as variables with high loading rates, further analysis picked SOM to represent organic matter and σ_c to represent mechanical properties. PC3 had FC and AW with high loading rates, FC was retained because of its high loading rate and communality. TN and C/N were the variables with high loading rates in PC4, with TN retained to represent nutrient factor. PC5 had only PWP as the variable with high loading rate, and it was dropped because FC has been selected, being a variable easier to determine compared with PWP. For this season, the MDS for the 0-10 cm surface layer were BD, FC, TN, OM and $\sigma_{c.}$

In 2012/2013 season, PC1 had BD, Pt, Ma, σ_c and Ic as high loading variables. BD was selected to represent permeation as it affects soil pore space, while σ_c was also retained as the soil mechanical factor. PC2 had TN and OM as variables with high loading rates, with both variables being retained to represent nutrient storage and organic matter factors, respectively. Mi, FC and AW were the variables with high loading rates in PC3, and Mi was dropped because it is related to PC1 factor while FC was retained as it controls AW. For this season, the MDS of the 0-10 cm layer were BD, σ_c, TN, OM and FC.

Organizing the MDS for the 0-10 cm layer showed that they are the same for each season, that is, BD, FC, σ_c, clay, TN and OM (Table 16). Similar PC analysis led to BD, FC, σ_c, TN and OM as the MDS for the 10-20 and 20-40 cm layers (Tables 17 and 18) for the initial and each growing season

2. Soil quality index (SQI)

The average values of soil quality index (SQI) of the sugarcane field under different tillage treatments at initial (October 2010) and after each of the 2010/2011, 2011/2012 and 2012/2013 growing seasons, as well due to the application of residue mulching and in the different soil layers are shown in Figures 22 and 23. Tillage did not significantly ($p<0.05$) affect the average values of SQI in all the seasons evaluated. Shortly after the imposition of tillage treatments in October 2010, the average value of SQI was about 0.27. At harvest of 2010/2011 growing season, average value of SQI was about 0.30, not much difference (about 8% more) from previous growing season. At harvest of 2011/2012 season, the average value of SQI was 0.24, a slight reduction (about 19%) compared to previous values. At the end of the 2012/2013 growing season, average SQI was 0.21, about 13% reduction compared with previous season. Regardless of tillage methods, residue mulching had no significant ($p<0.05$) effect on SQI during the two seasons of evaluation. For 2011/2012 growing season, average SQI were 0.38 and 0.34 for residue mulch and no mulch treatments, respectively. For 2012/2013 growing season, the average value of SQI was at par (about 0.33) (Figure 22).

Regardless of soil tillage treatments and considering no residue mulch treatment only, the quality status indicated by the average values of SQI in the 0-10, 20-40 and 40-60 cm soil layers of the sugarcane field is shown in Figure 23. Except for the 2010/2011 growing season, the average values of SQI significantly ($p<0.05$) differed among the soil layers with the superficial layer having the highest average values compared with subsurface. On seasonal basis, the average SQI values of the 0-10 cm slightly decreased after each growing season, as 4, 6 and 10% reduction were obtained in 2010/2011, 2011/2012 and 2012/2013 growing seasons, respectively, compared with the initial SQI value in 2010, while there was either an

increase or a decrease in the average values of SQI in both 10-20 and 20-40 cm layers, when compared with the initial value.

The relative contribution of each limiting factor to the mean soil quality index (SQI) values of the different soil layers of the sugarcane field at initial (October 2010) and after each of the 2010/2011, 2011/2012 and 2012/2013 growing seasons is shown in Figure 24. At initial (2010), pre-compression stress (σ_c) representing mechanical factor gave the highest contribution to SQI, about 34, 38 and 34% for the 0-10, 10-20 and 20-40 cm soil layers, respectively. The BD and FC, representing water retention and permeation factor followed, contributing about 30%. The lowest contributor was the nutrient storage factor (TN) and decreased with soil depth and was almost zero in the 20-40 cm layer. Similarly, the contribution from SOM decreased with soil depth. On seasonal basis, there was no discernible trend in relation to the contribution of each indicator to the mean SQI (Figure 24).

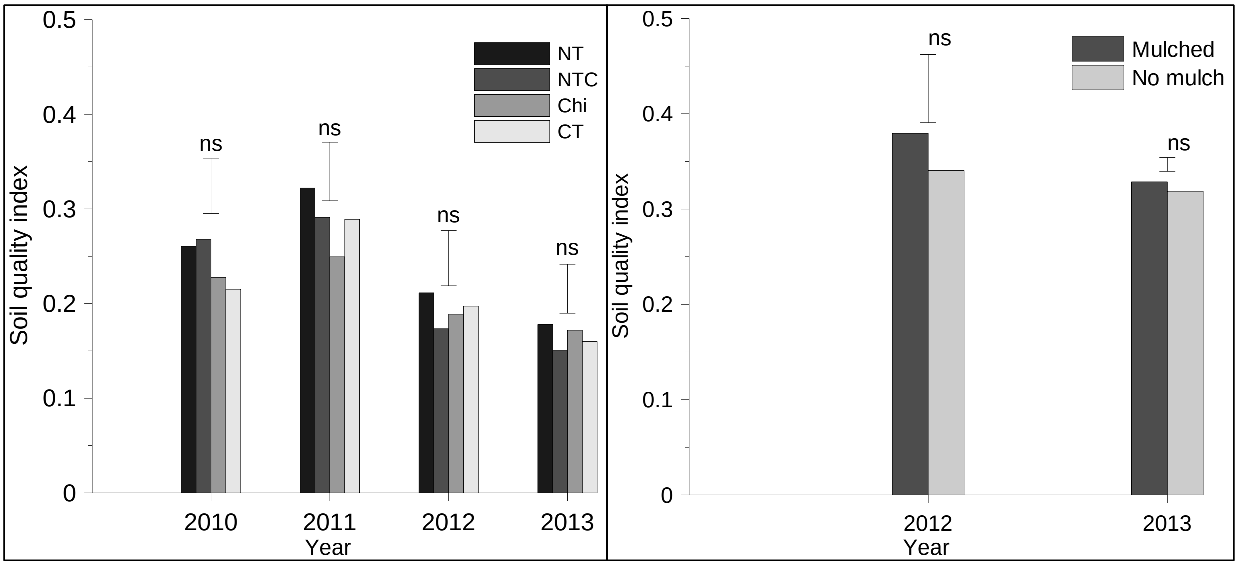


Figure 22. Mean soil quality index (SQI) values of the sugarcane field due to different tillage (left) treatments at initial (October 2010) and after each of the 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, Brazil. On the right shows the effect of residue mulching introduced during the 2011/2012 season.

ns: not significant at 5% probability level by Fisher's LSD test.

3. Management goals and soil quality indicators

The relationship between selected soil quality indicators and management goals, represented by sugarcane crop yield and soil function of profile water retention, is presented in Tables 19 and 20. The analysis of variance (ANOVA) showed that the correlation between selected soil quality indicators and sugarcane yield was not significant ($p<0.05$) for both seasons evaluated, while the values of the correlation coefficient, R, of the regression ranged from 0.63 to 0.78. During the 2011/2012 growing season, the correlation obtained from residue mulch treatment was higher (0.78) compared with no mulch treatment (0.63) (Table 19). The analysis

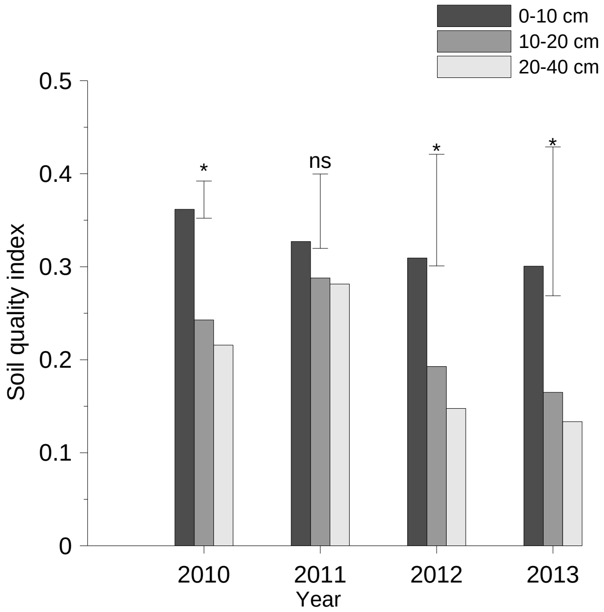


Figure 23. Mean soil quality index (SQI) values of the different soil layers of the sugarcane field at initial (October 2010) and after each of the 2010/2011, 2011/2012§ and 2012/2013 growing seasons at Santa Maria, Brazil.

§No residue mulch treatments were considered during 2011/2012 and 2012/2013 growing seasons.

*:significant and ns: not significant at 5% probability level by Fisher’s LSD test.

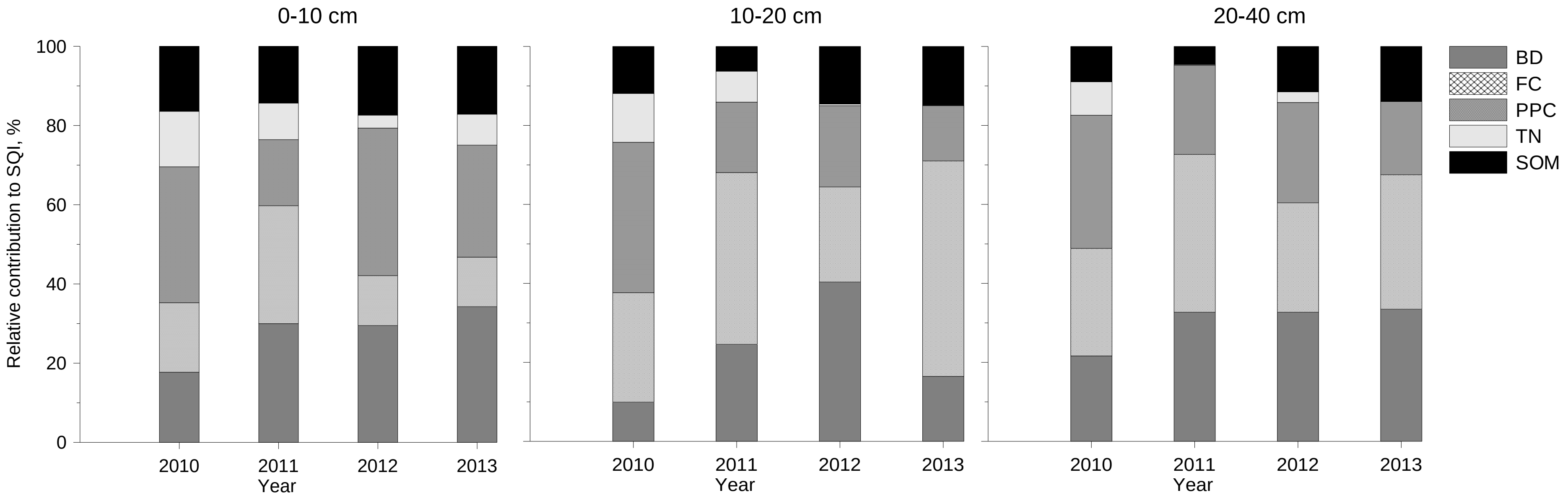


Figure 24. Relative contribution of each limiting factor to mean soil quality index (SQI) values of the different soil layers of the sugarcane field at initial (October 2010) and after each of the 2010/2011, 2011/2012 and 2012/2013 growing seasons at Santa Maria, Brazil.

Table 19. Relationship between selected soil quality indicators and management goal of sugarcane yield during 2010/2011 and 2011/2012 growing seasons at Santa Maria, Brazil.

Regression equation		
2010/2011 growing season	R	F-value
$Y = 78.3 - 10.0BD + 143.3FC + 0.02 + 4.39TN + 1.2SOM$	0.79	2.22 ^{ns}
2011/2012 growing season, without residue mulch		
$Y = 182.7 - 48.8BD - 28.2FC + 0.0003\sigma_c - 50.2TN + 38.7SOM$	0.63	1.31^{ns}
2011/2012 growing season, with residue mulch		
$Y = 151.5 + 14.4BD - 297.9FC + 0.10\sigma_c + 123.2TN - 7.8S2OM$	0.78	1.02 ^{ns}

Y: crop yield, ton/ha; BD: bulk density, g/cm^3; FC: field capacity, cm^3 cm^{-3}; σ_c: pre-compression stress, kPa; Clay, %; Silt, %; TN: total nitrogen, g/kg; SOM: soil organic matter, %.
R: correlation coefficient;
*significant and ns: not significant at 5% level of probability by ANOVA.

of variance (ANOVA) showed that the correlation between SWR and selected soil quality indicator was only significant (p<0.5) in no residue mulch during the2011/2012 growing. The correlation coefficient of the regression analysis ranged between 0.40 and 0.93 (Table 20).

4. Sugarcane yield and soil quality index (SQI)

The quantitative relationship between SQI and management goal of crop yield was made, using sugarcane yield as dependent variable and SQI as independent variable. The linear regression equations, R and p-value are given in Table 21. The correlation was generally low, ranging from 0.24 to 0.38, while the p values showed that the relationship was non-significant, however, the coefficients of SQI in the regression equations are positive. In 2011/2012 growing season, residue mulch

Table 20. Relationship between selected soil quality indicators and profile water retention of the sugarcane field during 2010/2011, 2011/2012, and 2012/2013 growing seasons at Santa Maria, southern Brazil.

Regression equation		
2010/2011 growing season	R	F-value
$WR = 2.17 + 0.80BD - 20.40FC + 0.001\sigma_c + 0.19Texture - 0.09TN + 1.82OM$	0.89	3.22^{ns}
2011/2012 growing season, without residue mulch		
$WR = 1.12 + 0.16BD + 3.15FC + 0.00001\sigma_c + 0.004Texture + 0.08TN + 0.27OM$	0.93	5.31*
2011/2012 growing season, with residue mulch		
$WR = 1.29 + 0.69BD + 1.50FC + 0.001\sigma_c - 0.008Texture + 0.13TN - 0.22OM$	0.86	2.37^{ns}
2012/2013 growing season, without residue mulch		
$WR = 3.10 - 0.12BD + 1.12FC + 0.00014\sigma_c - 0.003Texture + 0.96TN - 0.51OM$	0.75	1.07^{ns}
2012/2013 growing season, with residue mulch		
$WR = 2.26 + 0.29BD - 2.09FC - 0.00002\sigma_c + 0.017Texture + 0.33TN + 0.028OM$	0.40	0.14^{ns}

WR: profile water retention, mm; BD: bulk density, g/cm^3; FC: field capacity, cm^3 cm^{-3}; σ_c: pre-compression stress, kPa; Texture: clay and silt content, %; TN: total nitrogen, g/kg; OM: organic matter, %.

R: correlation coefficient

*significant and ns: not significant at 5% level of probability by ANOVA.

treatment had the higher performance in terms of coefficient (11.9 vs 8.0), R (0.38) and p-value (>0.212) compared with no mulch treatment (Table 21).

Table 21. Relationship between management goal of sugarcane yield and soil quality index (SQI) during 2010/2011 and 2011/2012 growing seasons at Santa Maria, southern Brazil.

Growing season	Treatment	Regression equation	R	P-value
2010/2011	-	$Y = 88.7 + 46.6SQI$	0.24	>0.421
2011/2012	Mulched	$Y = 107.7 + 11.9SQI$	0.38	>0.212
	No mulch	$Y = 104.3 + 8.0SQI$	0.30	>0.317

Y: sugarcane yield, ton/ha; SQI: soil quality index.
R: correlation coefficient; P-value: level of probability.

4.3 Temporal pattern of soil water storage

1. Classical statistics of temporal distribution of soil water status

The results of the classical statistics of soil water storage (SWS) and log matric potential, Ψ, in the 0-10, 10-20 and 40-60 cm soil layers are shown in Table 22. The temporal distribution of the SWS and Ψ in the different soil layers as well as the daily potential crop evapotranspiration (ET) and precipitation (P) for the two consecutive seasons are presented in Figures 25 and 26. The SWS increased with soil depth and was significantly highest, 51.7 and 55.3 mm, in the deepest layer, 40-60 cm in both 2011/2012 and 2012/2013 growing seasons, respectively. As already reported, the effect of residue mulch was statistically significant in all the soil layers in both growing seasons as significantly higher SWS was obtained from mulched treatments. The standard deviation (SD) from the mean value of SWS was highest, 4 mm in the 40-60 cm layer while it was highest (2 mm) in the surface layer, 0-10 cm in 2011/2012 and 2012/2013 growing seasons respectively. The SD values obtained from no residue mulch plots were higher, by 42.2-62.4% in 2011/2012 growing season and 22.1-90.7% in 2012/2013 growing season, compared to the values from residue mulch treatments.

The coefficient of variation (CV) was highest, 8% in 2011/2012 and 2012/2013

Table 22. Classical statistics of soil water storage, mm, and matric potential, kPa, in the different soil layers of the sugarcane field during the 2011/2012 and 2012/2013 growing seasons at Santa Maria, southern Brazil.

		Soil water storage, mm						Matric potential, kPa					
		---Soil depth, cm---											
	Stat.	0-10	10-20	40-60	0-10	10-20	40-60	0-10	10-20	40-60	0-10	10-20	40-60
Treatments	Para.	2011/2012 season			2012/2013 season			2011/2012 season			2012/2013 season		
Mulch	Mean	25a	26a	52a	26a	27a	55a	-17.9b	-15.8b	-20.9b	-14.4b	-13.3b	-8.17b
	SD	2	2	4	2	1	2	17	15	18	21	21	8
	CV, %	8	6	7	8	5	3	96	95	85	149	158	92
No mulch	Mean	24b	24b	47b	25b	26b	52b	-27.1a	-27.2a	-32.7a	-23.8a	-18.6a	-13.8a
	SD	3	3	5	3	2	3	23	24	19	26	22	15
	CV, %	12	10	10	10	7	6	84	86	55	110	118	105

SD: Standard deviation, CV: Coefficient of variation. Stat. Para.: Statistical parameters

Means of SWS followed by the same letters within the same column for a given year do not significantly differ at 5% probability level by two-tailed t-test.

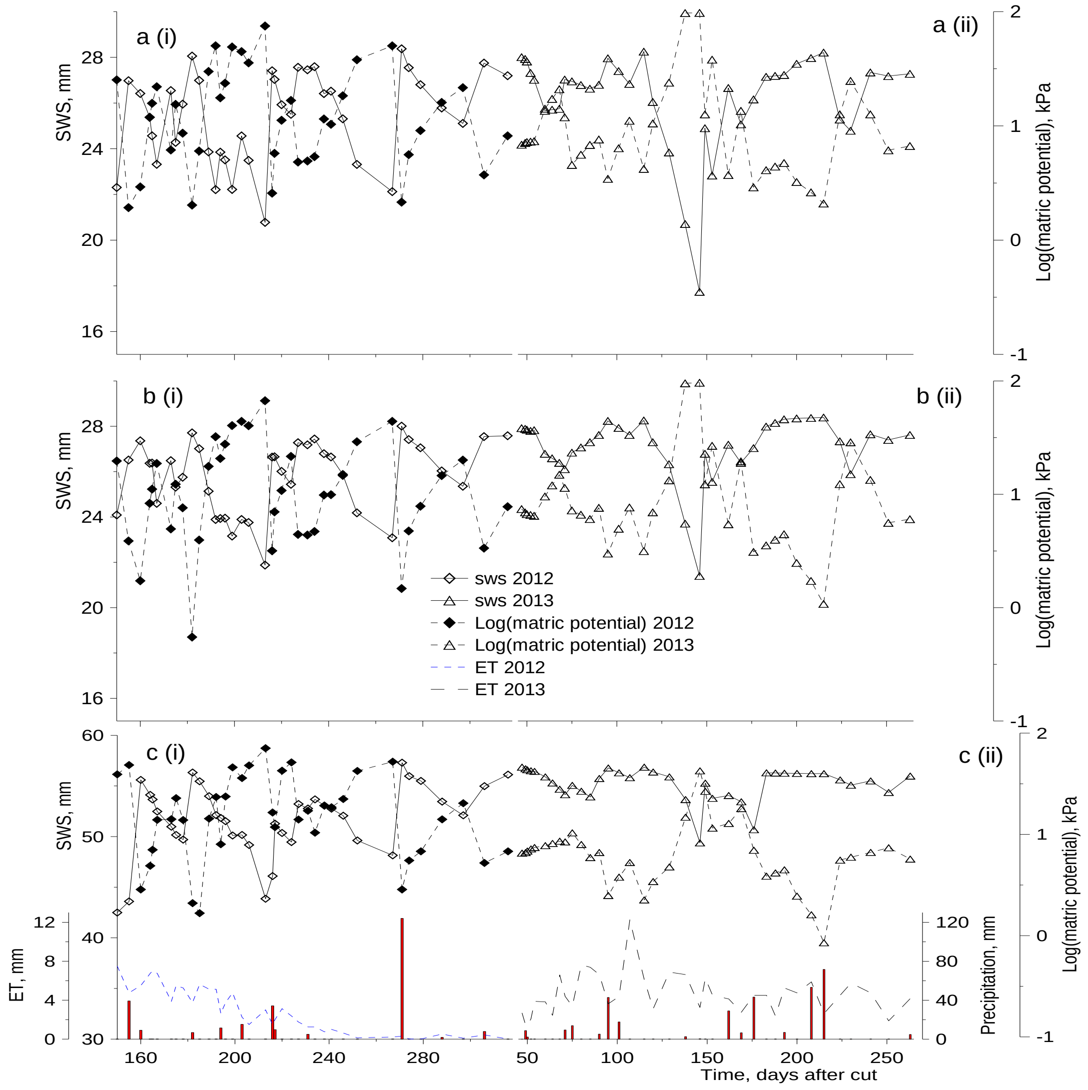


Figure 25. Temporal distribution of mean soil water storage (SWS) and log (matric potential) in the soil layers (a) 0-10, (b) 10-20 and (c) 40-60 cm from the residue mulched plots of the sugarcane field during the (i) 2011/2012 and (ii) 2012/2013 growing seasons at Santa Maria, southern Brazil.

ET: Crop evapotranspiration;

growing season, in the superficial layer (0-10 cm) of mulched plots and it was also highest 12 and 10% in the surface layer of no residue mulch treatment in the 2011/2012 and 2012/2013 growing seasons, respectively, while a decrease with soil depth was recorded and varying degree of time-to-time fluctuations was observed (Table 22 and Figures 25 and 26).

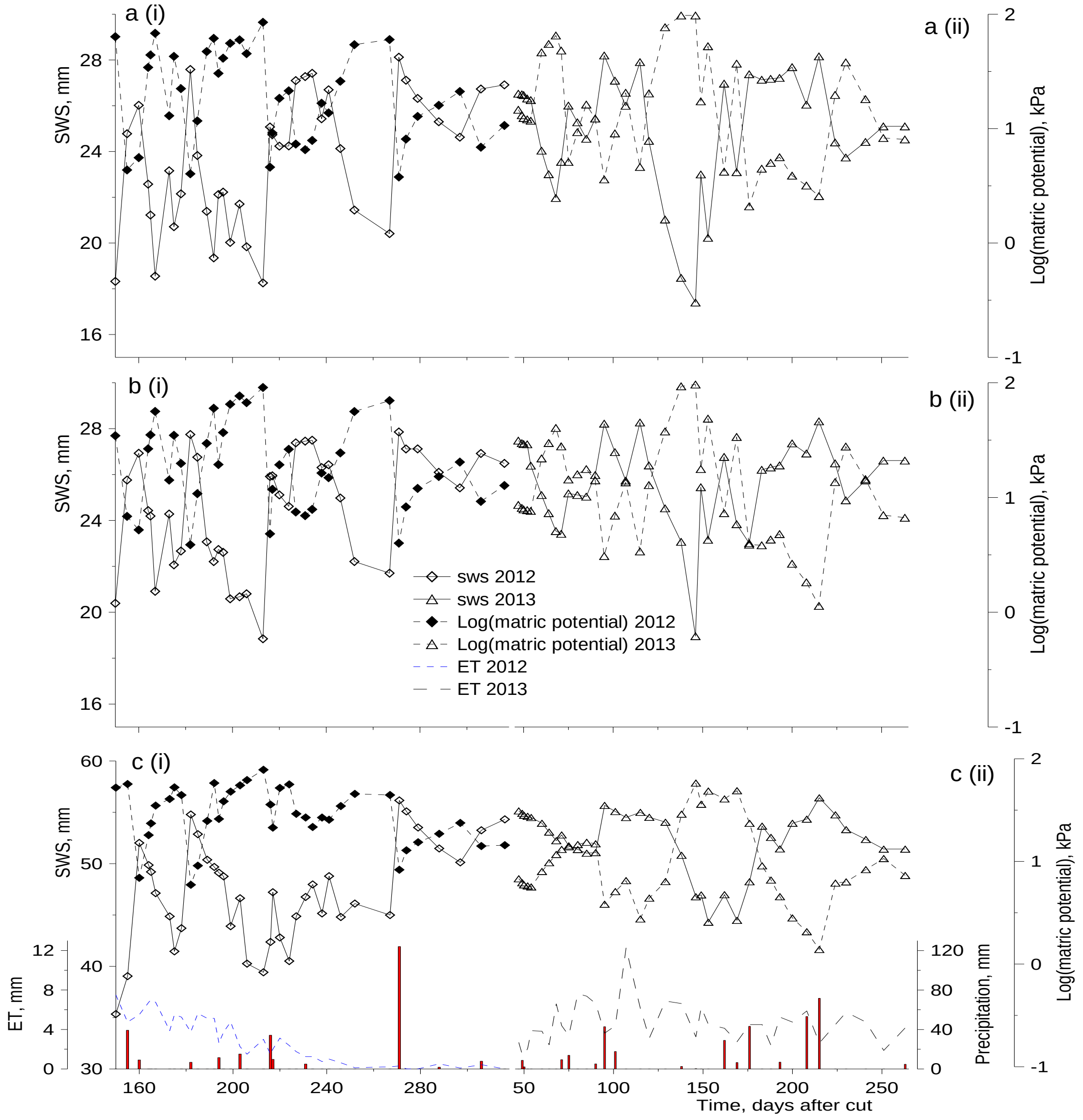


Figure 26. Temporal distribution of mean soil water storage (SWS) and log (matric potential) in the soil layers (a) 0-10, (b) 10-20 and (c) 40-60 cm from no mulch plots of the sugarcane field during the (i) 2011/2012 and (ii) 2012/2013 growing seasons at Santa Maria, southern Brazil.

ET: Crop evapotranspiration

The mean values of soil matric potential significantly differed due to residue mulching in both growing seasons. In 2011/2012 growing season, the highest mean value of soil matric potential, -32.7 kPa, was obtained from the 40-60 cm sub-surface layer , of no residue mulch plots while it was highest (-23.8 kPa) in the 0-10 cm surface layer of no residue mulch in

2012/2013 growing season. The highest value (23.5 kPa) of SD was obtained in the 10-20 cm soil layer of no mulch treatment in 2011/2012 growing season, however it was highest (26.3 kPa) in the 0-10 cm layer of no mulch treatment in 2012/2013 growing season. The SD values decreased with soil depth in both growing seasons. In 2011/2012 growing season, the CV varied between 55.2 and 95.7%, the highest value from the 0-10 cm surface layer and the lowest value from the 40-60 cm subsurface layer. In 2012/2013 growing season, the values of the CV were relatively higher compared to the values obtained in 2011/2012 season, the values ranging between -92.1 and -158 kPa (Table 22).

2. Autocorrelation and crosscorrelation analysis

The temporal autocorrelation (AC) lengths of soil water storage SWS and crosscorrelation (CC) coefficients between it and other soil-atmospheric variables are shown in Table 23. The results revealed that there was temporal autocorrelation of SWS measurements since the AC lengths, $\lambda > 1$ in all cases. In 2011/2012 growing season, the AC lengths of SWS ranged between1.55 and 2.55 lags, however the magnitude slightly increased with soil depth in both mulched and no mulch treatments.

In 2012/ 2013 growing season, the SWS distribution had AC lengths between ≈ 2 and 4 lags, while the magnitude of the AC lengths either increased or decreased with soil depth in both treatments. The ET and P time series data had AC length, λ, of 3 and < 1 lag, respectively.

From Table 23, there was correlation (CC) between SWS and log (Ψ) for the different soil depths, treatments and in both growing seasons. The CC length, λ_c, of SWS versus log (Ψ) ranged between ≈ 2 to 3 lags from both treatments in 2011/2012 growing season while it had values between 1 and ≈ 5 lags in 2012/2013 season. The CC lengths increased with soil depth and for any given soil layer, no mulch plots gave higher values. The CC functions of SWS versus ET behaved differently. In 2011/2012 growing season, the SWS correlated with ET only down to 20 cm soil layer, it decreased with soil depth and thus, did not correlate with ET in the 40-60 cm soil layer as $\lambda_c < 1$. However, in 2012/2013 season, the SWS correlated with ET in all the soil layers, with values of λ_c between 1 and ≈ 2. Also, there was no discernible trend in the calculated λ_c values (Table 23). Different behaviour was also observed from SWS versus P. Table 23 showed that SWS correlated with P in all the soil layers and

Table 23. The autocorrelation length ($\boldsymbol{\lambda}$) of soil water storage (SWS) and crosscorrelation length ($\boldsymbol{\lambda_c}$) between the SWS versus log matric potential [log (Ψ)], crop evapotranspiration (ET) and precipitation (P) in the different soil layers of the sugarcane field during the 2011/2012 and 2012/2013 growing seasons at Santa Maria, southern Brazil.

Soil layer, cm	Treatments	AC length, λ	CC, λ_c		
		SWS	SWS vs log(Ψ)	SWS vs ET	SWS vs P
		2011/2012 growing season			
0-10	Mulch	1.55	1.69	1.62	1.58
	No mulch	2.02	1.99	2.76	1.31
10-20	Mulch	2.17	2.30	1.39	1.83
	No mulch	2.27	2.37	1.96	1.67
40-60	Mulch	2.38	2.49	0.94	2.16
	No mulch	2.55	2.66	0.57	2.21
		2012/2013 growing season			
0-10	Mulch	2.34	1.52	1.51	0.83
	No mulch	2.34	1.72	1.35	0.69
10-20	Mulch	1.90	1.58	1.23	0.55
	No mulch	1.97	2.01	1.24	0.64
40-60	Mulch	2.51	1.10	1.47	0.83
	No mulch	3.90	4.70	1.81	0.67

AC: Autocorrelation length; CC: Crosscorrelation length.

treatments during the 2011/2012 growing season, with λ_c of 1 lag in the 0-10 and 10-20 cm layers and 2 lags in the 40-60 cm layer, indicating an increase with soil depth. Whereas, in 2012/2013 growing season, SWS did not correlate with P as λ_c was less than one (1) in all cases.

Table 24 shows the state equations and the coefficients of determination, R^2, calculated through linear regressions between scaled observed and estimated values of SWS using state-time analysis. The transition coefficients of the variables for each soil layer and treatments did not vary much, however, the coefficient of determination decreased with soil depth, except in the 40-60 cm layer of no mulch treatment in 2012/2013 season where it was highest. In all cases, the contribution of the previous values of precipitation was more than that of log (Ψ) and ET, indicating that the amount of water stored depends on the amount of rainfall that infiltrates into the soil matrix before it is available for evaporation, extraction by plants and transpiration.

3. Time series analysis of soil water status

The temporal patterns of the state-time analysis of the scaled SWS for the 0-10 cm layer of both treatments and growing seasons are presented in Figures 27 and 28. The continuous lines represent the scaled estimated SWS, the marked points are the scaled observed data while the shaded region is the 95% fiducial limits which take a plus or minus two standard deviation into consideration.

In the 2011/2012 growing season, the state-time equation of Figure 27 a(i) showed that about 62, 6, 7 and 23% of the previous soil water storage ($\mathrm{SWS}_{t\text{-}1}$), matric potential $[\log(\Psi)]_{t-1}$, crop evapotranspiration ($ET_{t-1)}$, and precipitation ($(P_{t-1)}$),contributed to the estimation of the present soil water storage (SWS_t) showing that the present value of SWS depends more on the previous measurements of itself than the previous observations of other variables. Comparing these results with the no residue mulching plots in Figure 27 b(i), the proportion of contribution of each variable are almost at par with those of mulched plots. For 2012/2013 growing season, the state-time equation of Figure 28 a(i) showed that about 70, 4, and 18% of the previous SWS, log (Ψ) and ET, and P contributed to the estimation of the SWS at present time t. Considering the temporal associations between SWS and other soil-atmospheric variables in this soil layer, about 96% of the variance of SWS was explained from the use of autoregressive state-time analysis [Figure 27 a(ii)] of the mulched plot while about 97% of the variance of SWS was explained from the use of the state-time series analysis [Figure 27 b(ii)] for no mulch plot in the first year of evaluation. For 2012/2013 growing season, these values were about 97% for both treatments (Figure 28). From Figures 27 and 28, only one (1) or two (2) points of the scaled measured values of SWS were outside the shaded area, (the 95% fiducial limits, in spite of using ±2 standard deviation, indicating that the state-time estimates are very good).

Table 24. State-time equations and coefficients of determination (R^2) of the scaled soil water storage (SWS) as a function of log matric potential [log(Ψ)], crop evapotranspiration (ET) and precipitation (P) in the different soil layers of the sugarcane field in 2011/2012 and 2012/2013 growing seasons at Santa Maria, southern Brazil.

Treatments	Soil layer, cm	State-time equation	R^2
		2011/2012 growing season	
Mulch	0-10	$SWS_t = 0.622SWS_{t-1} + 0.077[log(\Psi)]_{t-1} + 0.094ET_{t-1} + 0.183P_{t-1} + \omega_t$	0.96
	10-20	$SWS_t = 0.631SWS_{t-1} + 0.067[log(\Psi)]_{t-1} + 0.105ET_{t-1} + 0.174P_{t-1} + \omega_t$	0.97
	40-60	$SWS_t = 0.643SWS_{t-1} + 0.110[log(\Psi)]_{t-1} + 0.070ET_{t-1} + 0.125\,P_{t-1} + \omega_t$	0.66
No mulch	0-10	$SWS_t = 0.676SWS_{t-1} + 0.066[log(\Psi)]_{t-1} + 0.055ET_{t-1} + 0.184P_{t-1} + \omega_t$	0.97
	10-20	$SWS_t = 0.661SWS_{t-1} + 0.063[log(\Psi)]_{t-1} + 0.075ET_{t-1} + 0.182P_{t-1} + \omega_t$	0.96
	40-60	$SWS_t = 0.676SWS_{t-1} + 0.061[log(\Psi)]_{t-1} + 0.076ET_{t-1} + 0.142P_{t-1} + \omega_t$	0.96
		2012/2013 growing season	
Mulch	0-10	$SWS_t = 0.696SWS_{t-1} + 0.030[log(\Psi)]_{t-1} + 0.068ET_{t-1} + 0.194P_{t-1} + \omega_t$	0.94
	10-20	$SWS_t = 0.673SWS_{t-1} + 0.028[log(\Psi)]_{t-1} + 0.076ET_{t-1} + 0.209P_{t-1} + \omega_t$	0.88
	40-60	$SWS_t = 0.674SWS_{t-1} + 0.052[log(\Psi)]_{t-1} + 0.087ET_{t-1} + 0.150P_{t-1} + \omega_t$	0.92
No mulch	0-10	$SWS_t = 0.682SWS_{t-1} + 0.032[log(\Psi)]_{t-1} + 0.073ET_{t-1} + 0.206P_{t-1} + \omega_t$	0.94
	10-20	$SWS_t = 0.657SWS_{t-1} + 0.049[log(\Psi)]_{t-1} + 0.084ET_{t-1} + 0.185P_{t-1} + \omega_t$	0.93
	40-60	$SWS_t = 0.749SWS_{t-1} + 0.016[log(\Psi)]_{t-1} + 0.091ET_{t-1} + 0.112P_{t-1} + \omega_t$	0.98

SWS: soil water storage, mm; log (Ψ): log transformed matric potential, kPa; ω_t: state-time model error; t: present day; $t-1$: previous day.

R^2: coefficient of determination

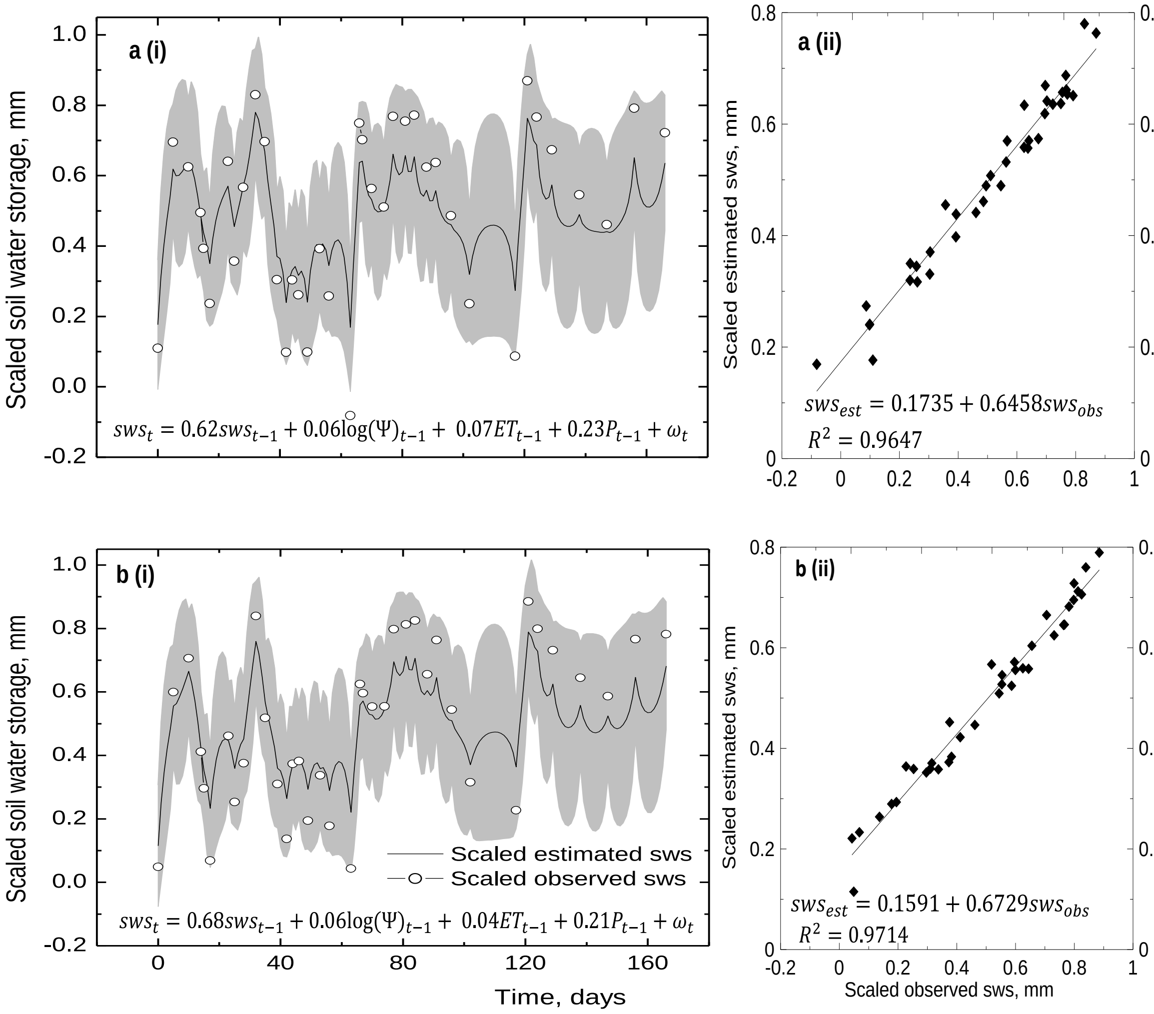


Figure 27. (i) State-time analysis and (ii) the coefficient of determination between scaled observed and estimated soil water storage values in the 0-10 cm soil layer of the (a) residue mulched and (b) no residue mulch plots of the sugarcane field in 2011/2012 growing season at Santa Maria, southern Brazil.

SWS_t: scaled present soil water storage, mm; SWS_{t-1}: scaled previous soil water storage, mm; $\log(\Psi)_{t-1}$: scaled previous log transformed soil matric potential, kPa; ET_{t-1}: scaled previous maximum cumulative evapotranspiration, mm; P_{t-1}: scaled previous cumulative rainfall, mm ; ωt: error term.

SWSest: scaled estimated soil water storage, mm; SWSobs: scaled observed soil water storage, mm

R^2: coefficient of determination

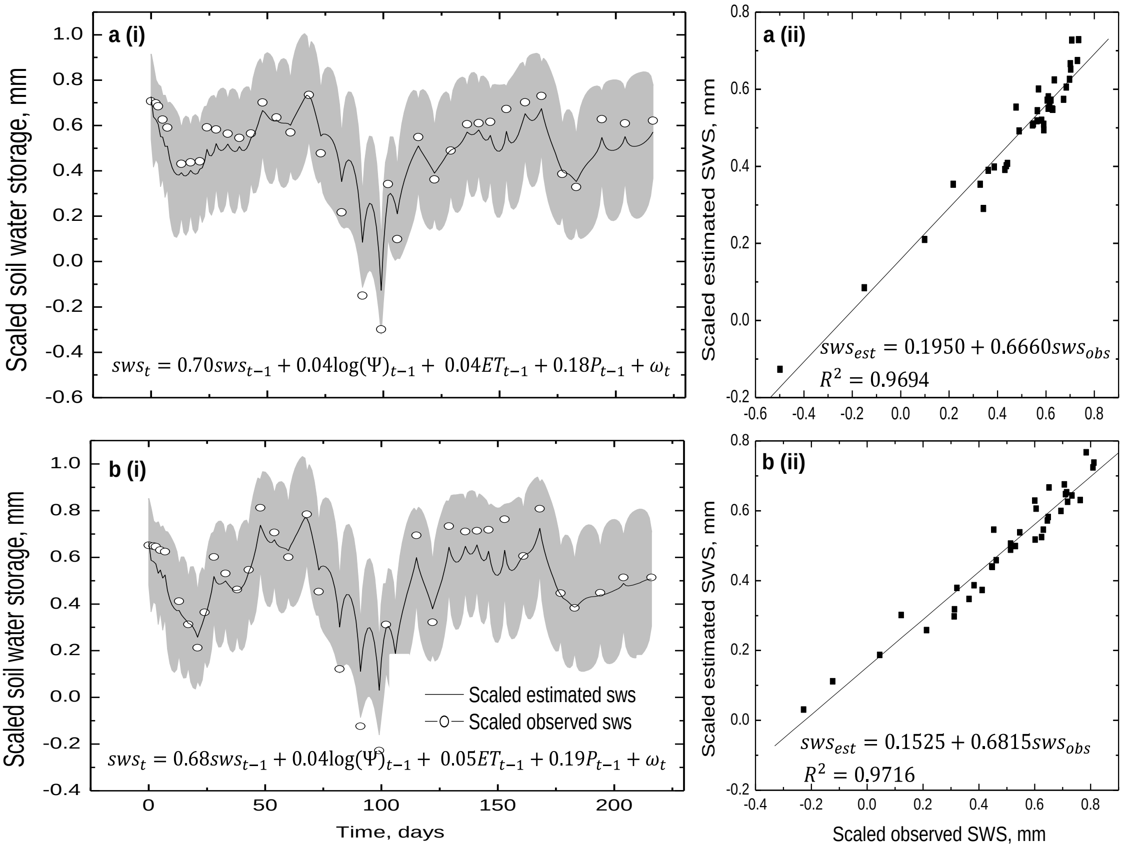


Figure 28. (i) State-time analysis and (ii) the coefficient of determination between scaled observed and estimated soil water storage values in the 0-10 cm soil layer of the (a) residue mulched and (b) no residue mulch plots of the sugarcane field in 2012/2013 growing season at Santa Maria. Brazil.

SWS_t: scaled present soil water storage, mm; SWS_{t-1}: scaled previous soil water storage, mm; log $(\Psi)_{t-1}$: scaled previous log transformed soil matric potential, kPa; ET_{t-1}: scaled previous maximum cumulative evapotranspiration, mm; P_{t-1}: scaled previous cumulative rainfall, mm ; ωt: error term.

SWSest: scaled estimated soil water storage, mm; SWSobs: scaled observed soil water storage, mm

R^2: coefficient of determination

4.4 Temporal pattern of soil temperature

1. Statistical comparison of daily soil temperature

The temporal distribution of the average daily soil temperature, $\bar{T}_s$, for the different soil layers and mulching treatments during the summer and winter periods of the sugarcane growing season in 2011/2012 are shown in Figures 29 and 30, respectively. The soil temperature data followed the climatic trend. Table 25 shows the results of the difference in mean, maximum, minimum and amplitude of the average daily soil temperature between residue mulch and no mulch treatments during the critical summer and winter periods of the 2011/2012 growing season.

Residue mulching significantly influenced average daily soil temperature. During the critical summer period, the difference in average daily soil temperature ranged between 1.3 and 4.1 ^{o}C, with the highest value from the 0-5 cm surface layer of Chi and CT treatments. The difference in maximum soil temperature was as high as 10.6 ^{o}C in the superficial layer of CT treatment which was almost at par with that of Chi treatment and as low as 1.7 ^{o}C in the 40-60 cm sub surface layer of NTC. The difference in minimum soil temperature had values between 0.2 and 2.0 ^{o}C while that of the amplitude of the thermal wave was between 0.5 and 4.7 ^{o}C. During the critical winter thermal conditions, the difference in the average daily soil temperature was not more than 3.2 ^{o}C; that of maximum temperature was between 0.6 and 4.3 ^{o}C while the minimum temperature did not differ more than 2.7 ^{o}C. The difference in amplitude was between 0.1 and 1.7 ^{o}C. For all the treatments, the average, maximum amplitude of daily soil temperature values decreased with soil depth except the minimum temperature that did not show any discernible trend (Table 25).

Table 25. Differences in average, maximum, minimum and amplitude of daily soil temperature (oC) of the different soil layers of the sugarcane field due to residue mulching during the critical summer and winter periods of 2011/2012 growing season.

		------------------------Soil layer, cm--------------------------				
Treatments	Stat. parameters	0-5	5-10	10-20	20-40	40-60
	Summer period					
Chi	Ave. daily temp	4.1a	3.8a	3.0a	2.7a	1.9a
	Max. temp	9.8	8	4.9	3.6	2.6
	Min temp	0.8	1.1	1.7	2	0.8
	Amplitude	4.5	3.5	1.6	0.8	0.9
NT	Ave. daily temp	2.8b	2.5b	2.3b	1.7b	1.3b
	Max. temp	7.2	4.8	4.1	2.8	2.6
	Min. temp	0.2	0.7	0.8	0.4	0.3
	Amplitude	3.5	2.1	1.7	1.2	1.2
CT	Ave. daily temp	4.0a	3.7a	3.3a	2.8a	2.2a
	Max. temp	10.6	7.4	5.1	3.5	3.4
	Min. temp	1.3	1.7	2	0.9	1.5
	Amplitude	4.7	2.9	1.6	1.3	1.0
NTC	Ave. daily temp	1.9c	1.8c	1.7b	1.5b	1.3b
	Max. temp	4.9	3.1	2.1	2	1.7
	Min. temp	0.8	1.2	1.1	0.8	0.4
	Amplitude	2.1	1.0	0.5	0.6	0.7
	Winter period					
Chi	Ave. daily temp	3.1a	2.7a	2.5a	2.2ab	2.1a
	Max. temp	4.3	3.4	2.9	2.4	2.3
	Min temp	1.8	1.9	2.1	2.1	2.0
	Amplitude	1.3	0.8	0.4	0.2	0.2
NT	Ave. daily temp	1.8b	2. 1b	1.1b	1.7b	1.4b
	Max. temp	3.1	2.8	3.0	1.9	1.6
	Min. temp	1.5	1.4	1.4	1.5	1.3
	Amplitude	0.8	0.7	0.8	0.2	0.15
CT	Ave. daily temp	3.2a	2.8a	2.6a	2.3ab	2.2a
	Max. temp	4.4	3.5	3	2.5	2.3
	Min. temp	1.9	2.1	2.2	2.2	2.1
	Amplitude	1.3	0.7	0.4	0.2	0.1
NTC	Ave. daily temp	2.7ab	2.5ab	2.3ab	3.2a	0.4c
	Max. temp	4.2	3.4	2.9	3.7	0.6
	Min. temp	0.9	1.3	1.6	2.7	0.2
	Amplitude	1.7	1.1	0.7	0.5	0.2

Mean values followed by the same letter in the same column do not differ at 95% significant level by Tukey test.
Chi: Chiseling tillage; CT: Conventional tillage; NT: No-tillage; NTC: No-tillage plus additional compaction.
Stat: statistics; Max. temp.: maximum temperature; Min. temp.: minimum temperature.

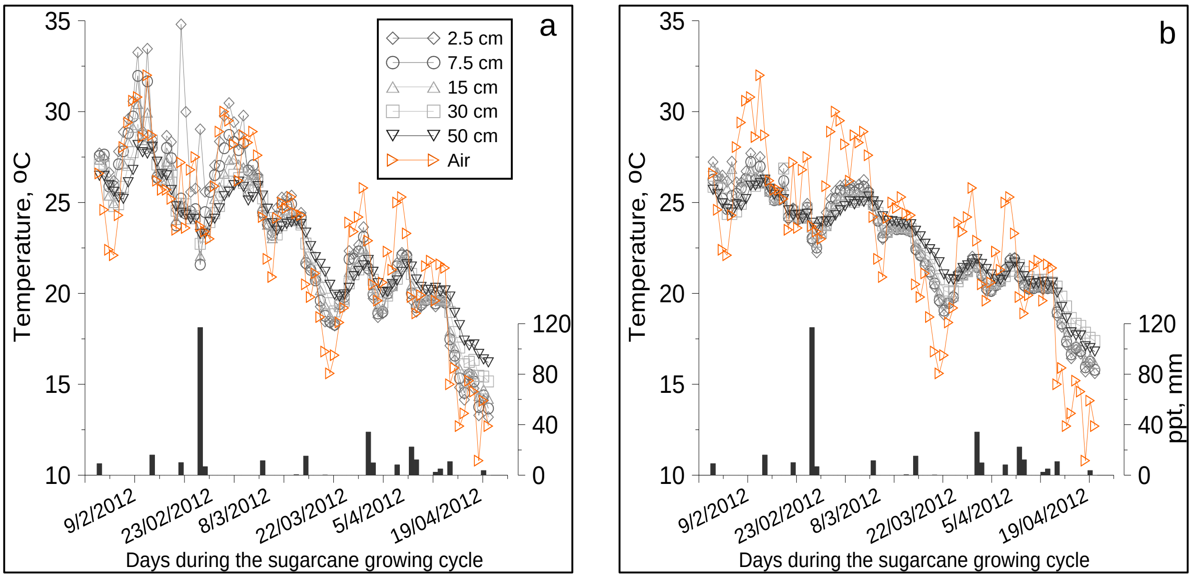


Figure 29. Temporal distribution of the average daily soil and air temperature in the different soil layers of the sugarcane field under (a) no mulch and (b) residue mulch treatments during the summer period of 2011/2012 growing season in Santa Maria, southern Brazil.

ppt: rainfall; The vertical bars represent the daily rainfall during each period.

2. Classical regression analysis of soil temperature

Regardless of the respective period of observation, the results of the classical regression of the average daily temperature from the average daily air temperature of the 0-5 cm soil layer of both residue mulch and no mulch treatments of the sugarcane field during the summer and winter periods of 2011/2012 growing season are shown in Figure 31. During the summer, no more than 83 and 87% of the variance of the measured average daily soil temperature data was explained by classical linear regression from no mulch and residue mulch treatments, respectively, soil temperature data that was explained by classical linear regression from no mulch and residue mulch treatments, respectively, during the winter period (Figure 31).

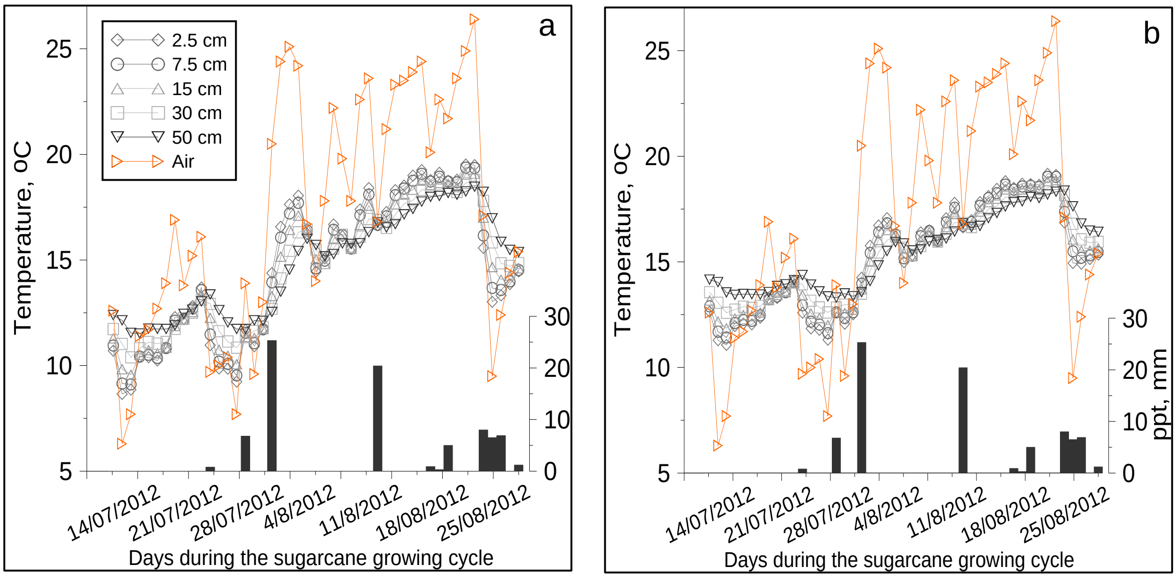


Figure 30. Temporal distribution of the average soil and air temperature in the different soil layers of the sugarcane field under (a) no mulch and (b) residue mulch treatments during the summer period during the winter period of 2011/2012 growing season in Santa Maria, southern Brazil.

ppt: rainfall; The vertical bars represent the rainfall amount during each period.

3. Effect of residue mulching on temporal covariance structure

To compare the covariance structure of the average daily soil temperature,$\overline{T}_s$, in time, isotropic variograms were computed. The $\overline{T}_s$ data of all the soil layers from both mulched and no mulch treatments were best fitted to spherical model during the winter, however during the summer, only the no mulch treatment had its $\overline{T}_s$ data best fitted to exponential model for all the soil layers while for the mulched treatment, the first three layers were fitted to exponential model and the 20-40 and 40-60 cm could only be fitted to non-bounded power and linear models, respectively. Figure 32 shows the semivariograms of $\overline{T}_s$ for the different soil layers, treatments and summer and winter periods of the 2011/2012 sugarcane growing season. The semivariograms computed across time during the two periods showed strong

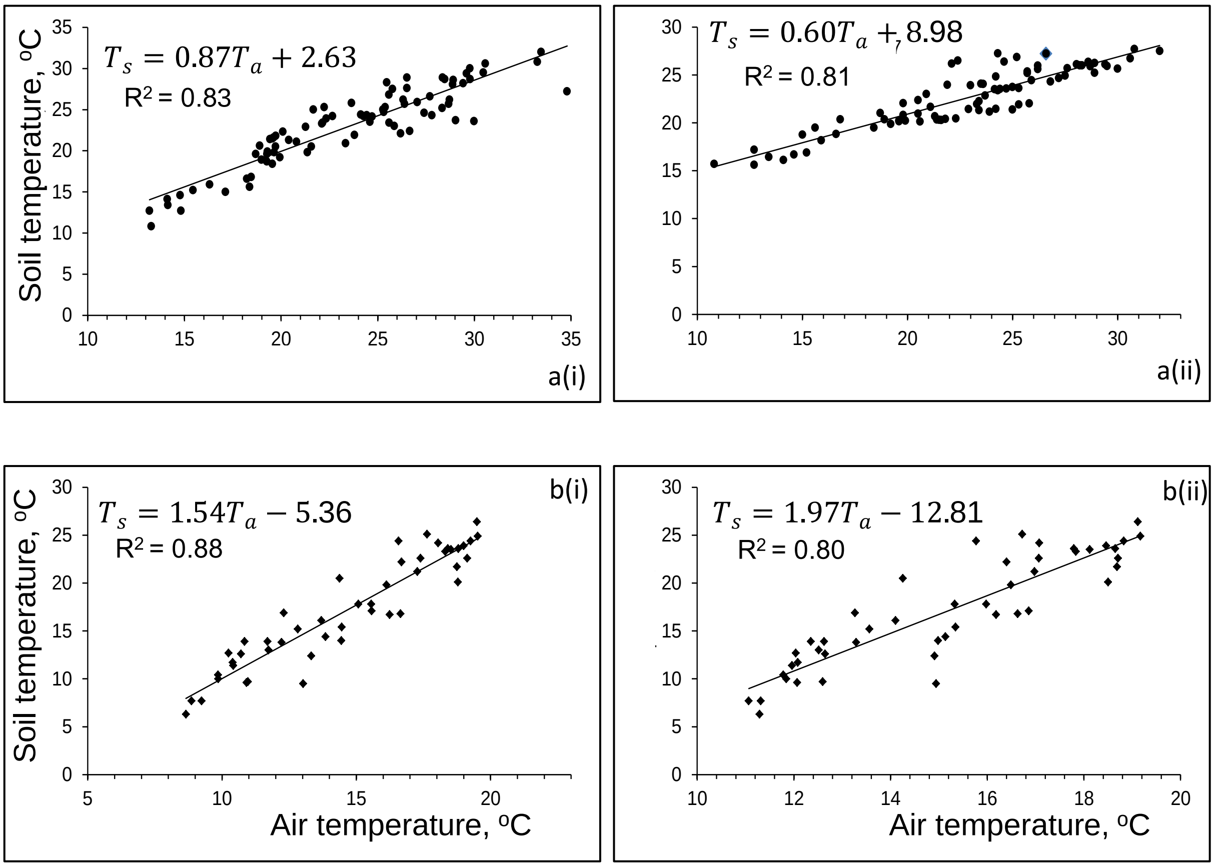


Figure 31. Classical linear regression and coefficient of determination of average daily soil temperature, Ts, of the 0-5 cm soil layer from the average daily air temperature, Ta, during the (a) summer and (b) winter periods of 2011/2012 sugarcane growing season at Santa Maria, southern Brazil.

(i) no mulch, and (ii) residue mulch treatments.

temporal correlation of T_s in all cases. The values of the temporal range of both the mulched and no mulch treatments ranged between 24 and 30 lags (in days) and increased with soil depth. The values were almost at par for the same soil layer of the two treatments (Figure 32a).

For the summer period and no mulch treatment, the temporal correlation range was between 13 and 26 lags, it neither increase nor decrease with soil depth. On the

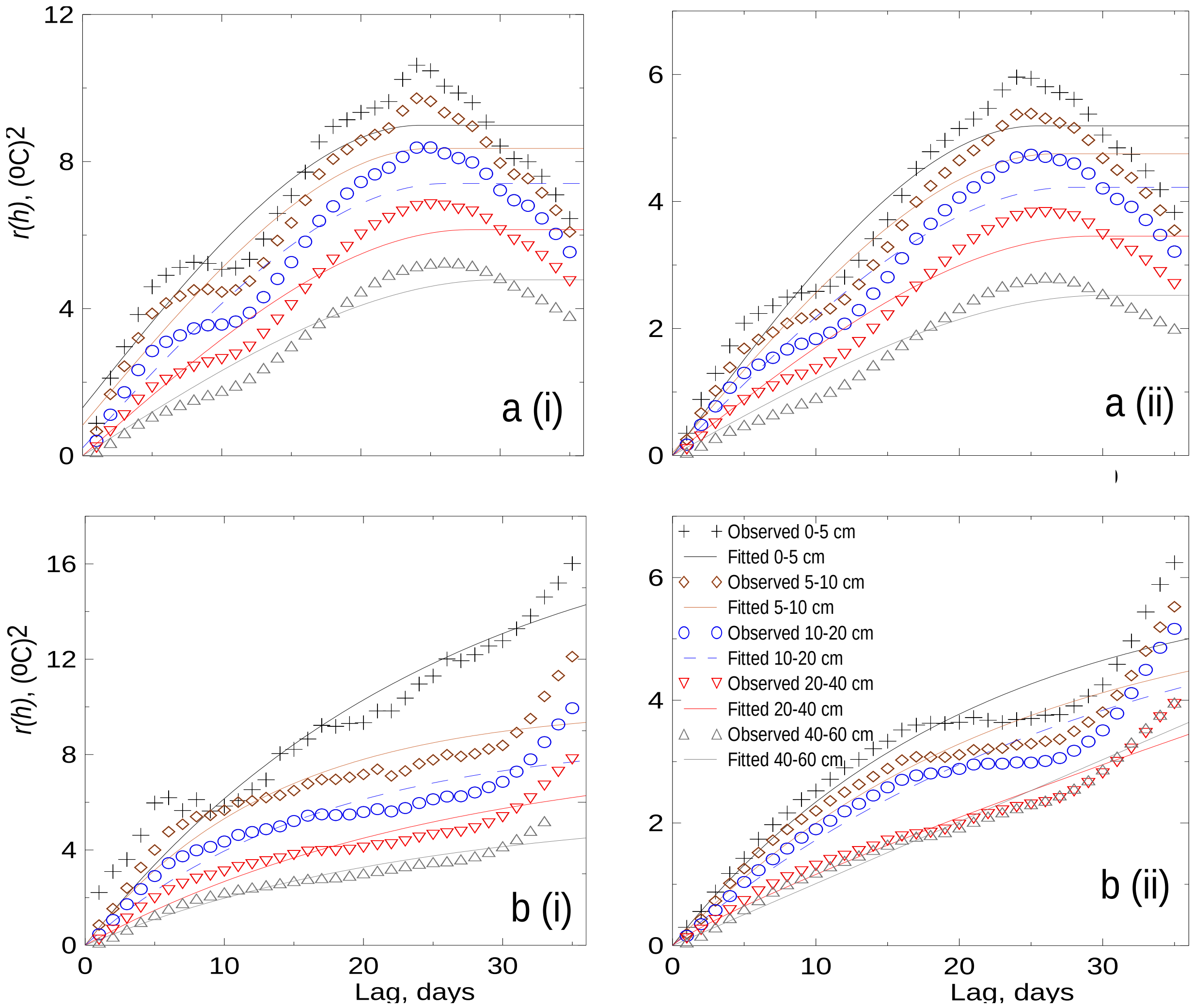


Figure 32. The semivariograms of the average daily soil temperature in the different soil layers of (i) no mulch and (ii) residue mulched plots of the sugarcane field during the (a) winter and (b) summer period of 2011/2012 growing season at Santa Maria, southern Brazil.

other hand, the residue mulch treatment had temporal range (between 13 and 17 lags) in the upper three layers whereas the deepest two layers did not have temporal range because no plateau was reached (Figure 32b). The values of the sill ranged from 2.52 to 8.99 (^{o}C)^{2} during the winter, between 4.17 and 18.81 (^{o}C)^{2} during the summer, and there was a decrease in the values of the sill with soil depth in all cases. Only the first three layers of no mulch treatment of winter period had nugget values, thus it was not possible to compare the nugget/sill ratio.

4. Time series analysis of soil temperature

Because of space and because the surface layer is where the partitioning of precipitation and energy takes place, only the state-time analysis of the 0-5 cm layer was performed. Prior to the state-time analysis, the autocorrelation (AC) and crosscorrelation (CC) analysis of $\bar{T}_s$versus air temperature (T_a) and rainfall (P) were determined and the CC functions are shown in Figure 33. While both the $\bar{T}_s$ and T_a autocorrelated, P did not autocorrelate. As expected, $\bar{T}_s$ did not correlate with the P (Figure 33a). Moreover, there was strong correlation between $\bar{T}_s$ and average daily T_a, where $\bar{T}_s$was related to T_a for more than eight and seven hours for both treatments during the summer and winter periods, respectively (Figure 33b). Thus, from these results, only the state-time analysis of variables $\bar{T}_s$ and T_a were made.

Because of the obvious monotonically decreasing and increasing trend in the data set (Figures 29 and 30) and strong temporal correlation between $\bar{T}_s$ and T_a, there is the potential of explaining how T_a would contribute to the estimation of $\bar{T}_s$ using applied statistical time series analysis (ASTSA). Figures 34 and 35 present the temporal patterns of the state-time analysis of the scaled $\bar{T}_s$ for the 0-5 cm layer of both treatments and periods. The continuous lines represent the scaled estimated $\bar{T}_s$, the marked points are the scaled observed data while the present soil temperature, $\bar{T}_{s_t}$. Comparing these results with that of mulched plots of Figure 34 a(ii), the proportion of contribution of previous $\bar{T}_s$ was higher while that of T_a was lower.

For the winter period, the state equation of Figure 35 a(i) of no mulch treatment indicated that about 97.6 and 2% of the previous $\bar{T}_{s_{t-1}}$, and $T_{a_{t-1}}$, respectively, contributed to the estimation of the $\bar{T}_{s_t}$. In the case of residue mulch treatment, the proportion of contribution of previous $\bar{T}_s$ was lower while that of T_a was higher (Figure 35 a(ii)).

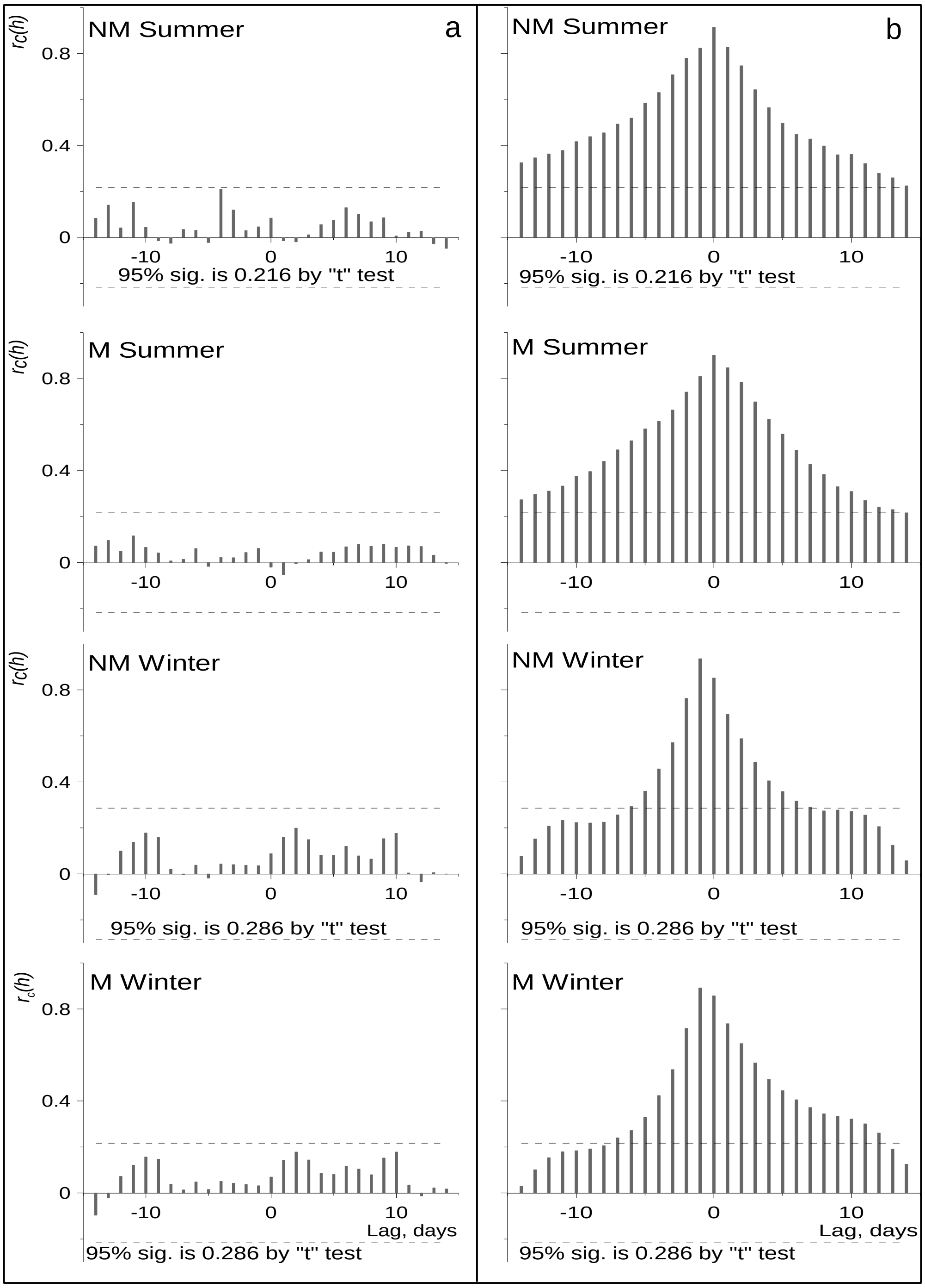


Figure 33. Cross-correlation functions, $r_c(h)$, of the average soil temperature of the 0-5 cm soil layer versus (a) precipitation, ppt, and (b) air temperature, T_a, of the no mulch (NM) and residue mulched (M) plots of the sugarcane field during the summer and winter periods of 2011/2012 growing season at Santa Maria, southern Brazil.

sig.: significant.

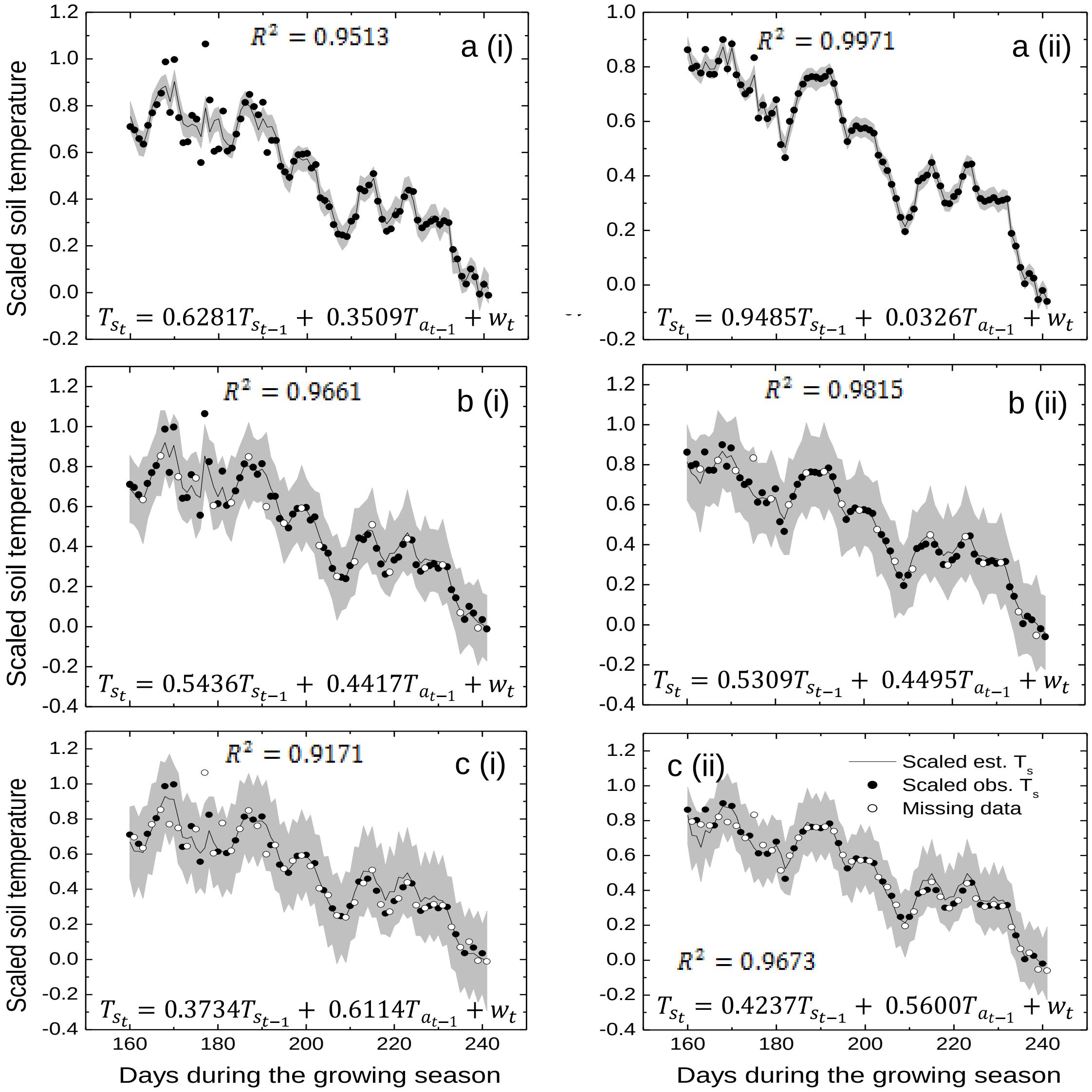


Figure 34. State-time analysis of scaled average daily soil temperature at 0-5 cm layer of the sugarcane field from (i) no mulch and (ii) residue mulched treatments during the summer period of 2011/2012 growing season at Santa Maria, southern Brazil.

(a), (b) and (c) indicate the results using the full data, 25% and 50% missing soil temperature data, respectively. The shaded region represents ± 2 standard deviation at 95% significant level.

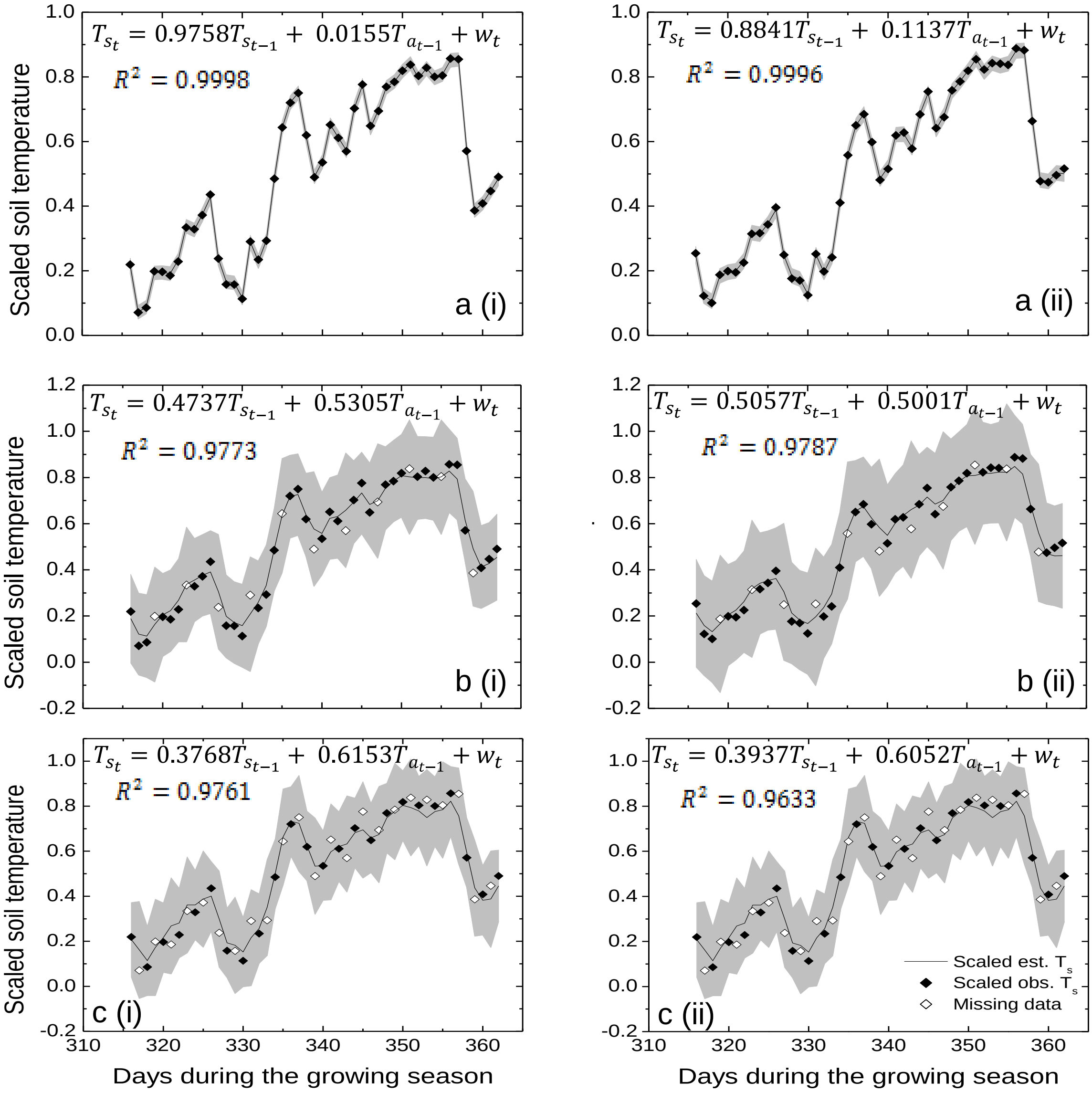


Figure 35. State-time analysis of scaled average daily soil temperature at 0-5 cm layer of the sugarcane field from (i) no mulch and (ii) residue mulched treatments during the winter period of 2011/2012 growing season at Santa Maria, southern Brazil.

(a), (b) and (c) indicate the results using the full data, 25% and 50% missing soil temperature data, respectively. The shaded region represents ± 2 standard deviation at 95% significant level.

Considering the temporal associations between $\bar{T}_s$ and T_a in this soil layer, about 95% of the variance of $\bar{T}_s$was explained by the use of autoregressive state-time analysis of no mulched plot while 99.7% of the variance was obtained from residue mulch treatment during the summer period (figure not shown). For the winter period, the coefficients of determination were 99.9 % for both no mulch and residue mulch treatments (Figures 34a and 35a). Comparing the classical linear regression and autoregressive state-time analyses to estimate $\bar{T}_s$ from T_a at 0-5 cm soil layer for each of the summer and winter period, the state-time analysis gave higher values of coefficient of determination (Figures 31, 34a and 35a).

The impact of omitting increasing numbers of measurement on the consistency and adequacy of the state-time analysis are shown in Figure 34 and 35. The results showed that when one in every four observations (25%) of the scaled $\bar{T}_s$ data (while those of T_a remained intact) was omitted, the magnitude of the transition coefficient of $\bar{\mathrm{T}}_{s_{\mathrm{t}-1}}$ decreased and that of T_a increased. When the omission was increased to every other observation (50%), the magnitude of the transition coefficient decreased further. The coefficient of determination slightly decreased from 95% to about 92% from no mulch treatment and 99.7% to 96.7% from mulched treatment during the summer period while the reduction was 99.9% to 97.6% and 99.96 % to 96.3% for the no mulch and mulched treatments, respectively in the winter period. In contrast, the width of the 95% confidence interval increased in comparison to when full data of $\bar{T}_s$ was used (Figure 34 (b and c) and 35 (b and c)).

5 DISCUSSION

5.1 Effect of soil management on soil quality indicators of sugarcane field

5.1.1 Bulk density and porosity

The soil property that is always altered by tillage operations is bulk density (BD) (CASSEL, 1982), and most alterations in the soil physical environment caused by soil mobilization are mediated through its effect on BD. This is proved as the BD negatively and significantly correlated with most of the soil quality indicators evaluated (Appendix I). The effect of the tillage methods on initial BD and porosity has been discussed by FONTANELA (2012). Thus the focus of the further study is on the residual effect of tillage and the imposition of residue mulching treatment. The slightly lower BD values obtained in the 0-10 cm surface layer at harvest of both 2011/2012 and 2012/2013 growing seasons compared with 2010/2011 growing season may be attributed to accumulation of soil organic matter from decayed and decomposed sugarcane roots (Table 8). This agrees with the findings of Abid and Lal (2008). Dalmago et al. (2009) found significantly lower BD in NT system in the surface layer as well as the last deeper layer compared with CT. They also attributed this to elevated organic matter, which contributes to higher and better soil aggregation (RAZAFIMBELO et al., 2008). The relatively high BD, about 1.79 g/cm^3, obtained below the surface layer indicate compacting subsurface layers, compared with the 1.75 g/cm^3 considered as threshold and within 1.75 and 1.85 g/cm^3 considered restrictive, which could cause visible deformation root morphology (REINERT et al., 2008). Beyond the critical BD (>1.85 g cm^{-3}), Reichert et al. (2009a) called it compacted layer or ‘no-till pan’ which can have both positive and negative effects on vital soil properties such as water flow and gaseous exchange, porosity, water retention, soil temperature, among others. Kaiser (2010) also reported a BD of 1.70 g/cm^3 in the 10-15 cm layer of the same soil. Reinert et al. (2008) also found BD values above 1.70 g/cm^3 in their study in a sandy loam soil. Irrespective of tillage method, residue mulch did not significantly influence the BD. This result contrast the findings of Blanco-Canqui et al. (2006) and Blanco-Canqui and Lal,(2007b) who reported lower BD in mulched plots under no till condition.

Soil porosity plays asignificant role in biological activity and hydrology of agricultural soils. Pores are of different size, shape and continuity and these features influence various soil processes (AIKINS and AFUAKWA, 2012). The total Pt of the0-10 cm surface layer did not differ significant due to tillage. Comparing the growing seasons, there was no discernible trend in the average values of Pt (Table 9). The slightly lower Pt obtained in the sub surface layers (10-40 cm) is attributed to the higher BD in this subsurface layer compared to the surface layer. This is expected as the Pt showed negative and significant correlation with the BD (Appendix I). The amount of macropores in the soil influences infiltration of water, gaseous exchange and root proliferation. The macroporosity (Ma) values of the 0-10 cm surface layer at harvest of both 2011/2012 and 2012/2013 growing seasons (Table 9) were almost at and above the 0.10 cm^3 cm^{-3} considered as critical to limit water movement and gaseous exchange (DREWRY et al., 2008). The Ma values obtained in this study were similar to the results of Dalmago et al. (2009) and Kaiser (2012) who studied similar soil. However, Dalmago et al. (2009) found significant differences in Ma between NT and CT systems but only in the 45 and 60 cm deeper layers. The authors said the difference was due to natural variability of the soil but not of management which is limited to the surface layers only (TORMENA et al., 2004). Abrue (2004) also found high Ma in the surface layer of a sandy loam textured soil under no-tillage. In this study, the high Ma in the 0-10 cm surface layer can be attributed to biopores created by decayed sugarcane roots. In the 10-20 and 20-40 cm sub surface layers (Table 9), the values were lesser than the threshold, indicating poor aeration and impedance to water movement. Kaiser (2012) also reported Ma values less than the threshold in the subsurface layer of the same soil. The reconsolidation process is also attributed to this, because during soil wetting by rainfall, the effective stress in the soil approaches zero, causing the soil matrix to collapse under its own weight, thus decreasing the size and number of macropores. Also the dynamic forces (adsorption and momentum) of water moving through the pores, which tend to compress the matrix. Similarly, there were few roots in these layers, thus limited root and biological activities to create biopores.

Microporosity (Mi) is a soil property that is responsible for water storage. In this study, the average values of Mi in the different soil layer and tillage treatments did not vary much compared with the initial values. This result agrees with the findings of Kaiser (2012) who reported that soil revolviment did not significantly affect pore with particle size less 50 μm. The author stated that these pores are less influenced by soil management but are controlled by soil texture rather than soil structure. In this study too, the Mi did not correlate with the BD (Appendix I).

Irrespective of tillage treatments, the Pt and Ma values of the 0-10 cm surface layer did not differ due to residue mulching, indicating that the time is rather too short for any discernible effect. Similarly, the effect of residue mulching was not significant on the Mi and the average values were almost at par for all the soil layers (Table 9). These results are in contrast with the findings of Blanco-Canqui and Lal (2007b) and Mahmood-ul-Hassan et al. (2013).

The non-significant differences in BD, Pt, Ma and Mi due to soil tillage and residue mulching as well as lack of interaction between tillage and residue mulching may be as a result of absence of tillage effect, especially in the surface layer. According to Silva (2003), Viega et al. (2006) and Reichert et al. (2009), the effect of soil mobilization disappear after a short period of about one year, after this soil consolidation takes place due to alternate wetting and drying cycles, raindrop impact and machine traffic. In this study, only the first two phenomena apply. Also, the short time of evaluation after the imposition of residue mulching could be attributed to this result.

5.1.2 Field capacity, permanent wilting point and maximum available water

The amount of water retained at field capacity (FC) depends primarily on capillary effects and pore-size distribution, and is therefore strongly influenced by soil structure while the amount retained at -1500 kPa or permanent wilting point (PWP) depends on soil texture and is controlled by adsorptive forces. The detail discussion of tillage methods on initial soil water retention at field capacity, permanent wilting point and available water can be found in Fontanela (2012). From Figures 15, 16 and 17, the soil water content at FC and PWP did not significantly differ under both tillage and residue mulching. For Kaiser (2012), the soil water content at FC was significantly highest in the surface layer of CT treatment compared with other tillage methods, however the FC was not significantly influenced in other soil layers. Reynolds et al (2002) did not find significant differences in soil water content (SWC) at FC and PWP between NT and CT systems in diverse soil types. According to the authors, the absence of significant difference between management systems on FC and PWP is due to the fact that SWC at PWP is determined by the clay content, which is unaffected by management, whereas the SWC at FC results from complex interaction among clay content, soil structure, bulk density and organic matter. In contrast, Dalmago et al. (2009) in their study on retention and availability of water to plants in soils under no-tillage and conventional tillage systems on the same soil type in southern Brazil found significant differences in SWC at FC between the management systems and all the soil layers whereas the SWC at PWP was only significant between the management systems in deeper layers, which they attributed to the natural variability of the soil. The author affirmed that soil texture and mineral composition have more effect on soil water retention than soil structure. In this study, the variation of soil water content at FC with soil depth is attributed to varying soil bulk density and Ma of the soil layers (Table 8 and 9).

The maximum water available (AWmax) content for root extraction and plant use under field conditions is controlled by soil structure and texture and the variation with time is determined by climatic conditions, type of crop, soil surface condition and management (ALLETTO AND COQUET, 2009). Any measure that either increase or decrease soil water content at both FC will influence the AWmax. The AWmax positively and negatively correlated with the FC and PWP, respectively (Appendix I), indicating any increase in water soil content at PWP will reduce the amount of water available for plants. Tillage did not significantly influence the AWmax in all the soil layers and growing seasons. This result agrees with the result from both the FC and PWP. Also, the soil was not mobilized after the first application in 2010, thus none of the tillage methods dominate over AWmax. Similarly, the clay content in these soil layers is almost the same (9-11%), hence the maximum available water content is almost at par for all the soil layers (Table 10). This result contradicts that of Kaiser (2010) who found significantly lowest AWmax in the surface layer of CT treatment and in the 15-20 cm layer of Chi treatment. Dalmago et al. (2009) found higher AWmax in NT treatment compared with CT treatment only in the 2.5 and 7.5 cm surface layers while AWmax was higher in CT than NT from 15 cm down to 75 cm deeper layers evaluated. Likewise, Bamberg et al. (2011) in their study on temporal changes in soil physical and hydraulic properties in strawberry fields in Brazil found increase in AWmax with time. The authors attributed this to decreased Ma and increased Mi, indicating that the soils changed their structure to a more packed configuration.

There was no significant effect of residue mulching on AWmax (Table 10). Although it is expected that soil organic matter, an agent for improved soil structure and water availability, would increase due to residue mulching, but this was not significantly achieved in this study, indicating more time is needed. This result also agrees with the previous results of the significant effect of residue mulching on BD, Pt, Ma and Mi.

5.1.3 Soil organic matter, Cpool, C/N ratio and total nitrogen

For all soils, organic matter is central to the functioning of many physical, chemical and biological processes in the soil, such as nutrient storage and exchange capacity, soil structural stability and porosity, water availability, degradation of pollutants, among others (BAYER and MIELNICZUK, 1999). In this study, the SOM showed a significant positive correlation with the porosity (total-, macro- and microporosity) and available water while the correlation was negative and significant with the BD (Appendix I). The increased SOM content and Cpool of the surface layer of no till plots (NT and NTC) compared with tilled plots (Chi and CT) over the seasons were due to decay and decomposition of weeds and sugarcane roots (Table 11). The lower values of these variables in the surface layer of tilled plots (CT and Chi) may also be attributed to carbon loss via CO_2 emission as also reported by Al-Kaisi and Yin (2005). The lower SOM content and Cpool in the subsurface layers of the tillage treatments, except CT in 10-20 cm layer in 2010/2011and 2011/2012 growing seasons, was due to the effect of no plant residue and low root biomass in those layers, which could have contribute to organic carbon build up. For the CT treatment with increased SOM content and Cpool, it could be due to inversion of surface layer. Etna et al. (1999) explained that two factors could lead to higher SOM concentration due to CT: (a) soil exchange leading to a net transportation of soil organic carbon to subsurface layers, and (b) incorporation of crop residues. As expected, the increased SOM of the surface layer was due to residue mulching resulted from more availability of crop residue for decaying and decomposition processes whereas there was no effect in other layers. Similar results were reported by Blanco-Canqui and Lal (2007a).

The non-significant effect of the treatments on SOM and Cpool agrees with the report by Al-Kaisi and Yin (2005) who reported that their 3-yr NT studies on tillage and residue effect on soil carbon and carbon dioxide emission in corn-soybean rotations at Iowa, USA was not enough for significant carbon sequestration.

Although the physical properties of soils are important, nutrient concentrations, such as TN, in the soil are more important for soil fertility and management goal of crop productivity. In this soil, the initial TN content was generally low (Table 11), a little above the lower threshold of 0.5% in the surface layer, already at and below the threshold level in the 10-20 and 20-40 cm layers, respectively (YAO et al., 2013). Although NT treatment had the highest total nitrogen throughout the evaluation period, however its values generally decreased in all the tillage treatments and soil depth with time, resulting in elevated C/N ratios. The result from NT treatment agrees with the findings of Wright et al. (2007) who reported that TN was about 33% higher in NT treatment than CT. The seasonal reduction TN may be due to extensive use of soil nitrogen by sugarcane (AUSTRALIAN, 2008) as a result of its high biomass production. This trend has negative implication on both plant and soil functions. Thus, low level of N will not only inhibit the above-ground biomass and yield, but also influence root biomass negatively as long and thinner roots will result, which will subsequently reduce the volume of soil explored. Consequently, this will impair the functional capacity of the soil due to decreased soil organic carbon and other rhizosphere activities (SHARMA et al., 2008). The increase in C/N ratio (even with the retention of crop residues) is an indication that crop available nitrogen is being tied up (immobilized), thus, the nitrogen becomes unavailable for plant use unless nitrogen fertilizer is added to the soil to decrease the C/N ratio (BLACK et al., 2010).

5.1.4 Soil mechanical properties

Pre-compression stress (σ_c) is an indicator of soil compaction and refers to the bearing capacity of the soil bulk, depending on the properties of individual aggregates and their architectural organization (BLANCO-CANQUI et al., 2005) and highly influenced by soil water content and SOM content of the surface layer (REICHERT et al., 2009a). As reported by Fontanela (2012), the low initial value of σ_c of the 0-10 layer of CT and Chi treatments (Figure 18) was due to soil mobilization. The recently tilled layer tended to be structurally fragile because of the low σ_c and thus, reduced capability to support a load (DEBIASI et al., 2008). Thereafter, consolidation takes place (REICHERT et al., 2009c) caused by alternate wetting and drying cycles until the establishment of new structural equilibrium (LEIJ et al., 2002) with increase in soil internal strength (HORN and BAUMGARTL, 2002). Thus, the increasing trend obtained after each season indicate increased soil internal strength and capacity to withstand external load, although this will depend on the kind and nature of the applied load as well as soil moisture condition. Horn (2004) reported temporal variability of σ_c, although the authors applied tillage for seven consecutive years as against the single application of tillage in this study. The low values of σ_c obtained for the 0-10 cm layer compared with other layers is consistence with the low BD as reported. The correlation analysis also showed that the BD positively and significantly correlated with the σ_c (Appendix I). The absence of no tillage operation may also explain the non-discernible trend with the different tillage methods.

On the other hand, the compression index (I_c) is an indication of soil susceptibility to compaction. The average initial values I_c in the 0-10 cm layer of the tillage plots were highest initially (FONTANELA, 2012), indicating high susceptibility to compaction compared with subsurface layers. In general, the highest values of I_c in the surface layer (Figure 19) showed the susceptibility to compaction compared to other layers. This result is also consistence with the increased pre-compression stress with soil depth, considering the significant indirect relationship between σ_c and I_c (Appendix I). Similarly, there was no consistency among the different tillage treatments in terms of highest or lowest values due to no soil mobilization (Table 12). Thus it is essential to apply tillage every year, using the same equipment to be able to obtain significant effect, especially the surface layer.

Considering the effect of residue mulching (Figures 20 and 21), the contrasting results was unexpected as regard the presence of surface mulch in absorbing and reducing the energy of raindrop and machine traffic, respectively on soil surface. Thus, further investigation is required to verify this observation.

5.1.5 Degree of compaction

The degree of compaction (DC) is a function soil bulk density, found to be highly correlated with soil texture, especially clay content. According to Reichert et al. (2009a), the

DC has been established as an efficient parameter to identify soil compaction affecting crops resulting from annual tillage (HANKASSON, 1990) or for soils not disturbed annually (HAKANSSON and LIPIEC, 2000). Shortly after tillage in 2010, the DC values of the 0-10 cm surface layer in CT and Chi treatments (Table 13) were below the range of the optimum DC of 77-88% for crops proposed by Suzuki et al. (2007) while in NT and NTC treatments, the values were respectively, at and above the maximum DC of 90% proposed by Reinert et al. (2008). Although the DC values of the surface layer were within the range proposed, however, the DC values of the 10-20 and 20-40 cm sub surface layers were generally above the maximum DC of 90% (REINERT et al., 2008), indicating some degree of subsoil compaction. Vasconcelos et al. (2014) working on physical quality of Yellow Oxisol in a coastal plain under different management systems in sugarcane in Brazil also found DC values, as high as 91% for the 0-20 cm layer and up to 99% for the 20-60 cm sub surface layer. Although this soil is of more clay compared to this soil. Gubiani (2012) working on the regularity of the corn crop response to soil compaction of an Oxisol in southern Brazil found that 61% of the sampled soil at 7 and 25 cm under compacted no-tillage (NTC) treatment had degree of compaction equal to or greater than 90%. High DC as observed in the subsurface layer of the sugarcane field has implications on soil quality indicators and processes such as water dynamics, aeration, nutrient cycling and thus could limit root growth and crop development, especially during periods of prolonged droughts. Suzuki et al. (2007) stated that a high degree of compaction can reduce soil porosity and aeration, increase soil bulk density and resistance to penetration, and thus impedance to normal root growth and crop development. Silva et al. (2014) affirmed that impervious layer, especially when close to the surface layer, could delay water infiltration into the soil, promoting surface runoff and erosion. In short, the authors stated that there should be no layer, whether surface or subsurface, being characterized by high compaction degree because steady-state infiltration rate largely depends on saturated hydraulic conductivity of the impervious layer (HILLEL, 1998).

The application of residue mulching did not influence the DC of both the surface and subsurface layers (Table 13), this is expected because the DC is a function of the BD and the BD was not influenced by residue mulch application. As already stated, the relatively short-term of evaluation after residue mulch application was not enough to have any significant effect on the DC.

5.1.6 Soil water retention

Soil water retention under field conditions is a function of soil structure and the temporal variation being largely determined by climatic conditions, crop growth stage, soil surface condition and management (KAISER, 2010). The slightly higher average SWR in the subsurface layers of all the treatments and growing seasons is attributed to soil texture and mineral composition. In this soil, the clay content, which is responsible for water storage, slightly increases with soil depth.

Among the tillage methods, there was no significant difference in the average values of SWR in each soil layer as well as the total soil profile water retention (SWR) in all the seasons. Even in the first growing season (2010/2011) when the soil was mobilized, none of the tillage methods dominates over the other on SWR (Table 14). Kaiser (2010) working on the same soil, reported that NT did not more water compared with other tillage treatments.

There was no significant difference in the average values of SWR in all the soil layers as well as total SWR between residue mulched and no mulch treatments during both seasons evaluated, however residue mulch soil seems to have slightly higher SWR (Table 14). The reason for the non-significant effect of residue mulch on soil water dynamics is due to short-term effect. One of the main effects of retaining a mulch blanket over the soil surface is soil water conservation by reducing evaporation from the surface layer (TOMINAGA et al., 2002). Lentz and Bjorneberg (2003) and Jordan et al. (2010) asserted that the retention of crop residue on the soil surface is a conservation management practice aimed at better management of water, prevent surface sealing, increase infiltration, improve aggregation and porosity and control erosion. Duiker and Lal (2000) reported that residue mulching, apart from enhancing soil quality, possesses the potential to increase infiltration and mitigate evaporative losses. The decomposition of crop residue leads to increase in soil organic matter and soils with higher organic matter also have higher water holding capacity, especially in sandy and clay soils, due to its effect on soil structure and its higher specific surface area (RAWLS et al., 2003), which is a favorable factor for improving the availability of water to plants. Blanco-Canqui and Lal (2007b) concluded that the greater water retention capacity of mulched treatment is explained by the high water absorption capacity of residue-derived organic materials. Other studies have reported similar results (e.g. PERES et al., 2010; MAHMOOD-UL-HASSAN et al., 2013).

The soil water dynamics of the first growing season, 2010/2011, differed compared with both 2011/2012 and 2012/2013 growing seasons, however for both 2011/2012 and 2012/2013 growing seasons, the soil water dynamics was more or less similar. The differences in seasonal values of SWR of the different treatments followed the course of climatic conditions, especially rainfall distribution and evaporative demand of the atmosphere and differences in soil wetting and drying cycles (Figure 14). The differences in soil wetting and drying cycles is attribute to rainfall distribution which is rarely the same for two consecutive growing seasons. During the 2010/2011 growing season, 1204 mm of rainfall was received while the amount were 1002 and 1639 mm during the 2011/2012 and 2012/2013 growing seasons, respectively (Table7). Although some months (between November and February) were characterized by higher evaporative demand at the expense of limited rainfall during the early growth stage, however the physiological stress due to water deficit was limited. This may be attributed to water availability in the compacted subsurface layers. In addition, some roots of the sugarcane ratoon may have explored these compacted layers and maintain good contact during period of sufficient water supply by rainfall.

5.2 Sugarcane yield

There was no discernible trend in sugarcane ratoon yield at harvest of 2011/2012 with respect to the different tillage treatments in comparison to previous crop yield. The total ratoon yield at harvest of 2011/2012 was higher than previous season (425 vs 410 tonnes/ha) Table 15). The average sugarcane ratoon yield values obtained in this study were similar to yields reported in literature. Benett et al. (2012) in a study on the quality and productivity of sugarcane crop and ratoon in Brazil found higher ratoon yield (90-105 tonnes/ha) than crop yield (87-99 tonnes/ha). Carvalho et al. (2013) also reported similar ratoon yield in the range of 93-104 tonnes/ha. Although Singh et al. (2008), working on the effect of agro-technological manipulations in improving the productivity of cane under multiratooning system in South Africa, found a maximum cane lower ratoon yield of 81 tonnes per hectare. The difference in yield may be as a result of variation in soil type, climatic conditions and crop specie.

Higher ratoon yield was obtained from residue mulch treatment compared to no mulch treatment, although the difference was not significant. Nevertheless, this is an indication of positive effect of mulching. Ball-Coelho (1993) found 17 tonnes/ha cane yield under mulch treatment in multiratooning system over trash burn treatment. He concluded that conserving trash and its application to improve soil fertility and productivity should be the goal. However, Oliver and Singels (2012) studying the effect of crop residue layer on evapotranspiration, growth and yield of irrigated sugarcane in South Africa found lower sugarcane yield in mulched plot compared with bare soil of both crop and ratoon. They said that crop residues following green cane harvesting could have little or negative responses in super-humid and low-temperature regions.

5.3 Soil quality assessment

Soil quality index (SQI) is a tool that helps quantify the combined physical, chemical and biological response of soil to soil and crop management practices (MASTO et al., 2007) and provide necessary integration of information for farmers and land managers to make decisions about the complex issues involving agroecosystem management (ANDREWS and CARROLL, 2001). The different tillage treatments did not significantly influence the SQI, however some degree of superiority could be inferred with respect to SQI in each growing season. At harvest of 2010/2011 season, the order was NT>NTC>CT>Chi; NT>CT=Chi>NTC at harvest of 2011/2012 season and NT=Chi>NTC=CT at the end of 2012/2013 season (Figure 22). Thus, NT treatment can be judged as maintaining its position throughout the evaluation period. The relatively high SQI from NT treatment resulted from undisturbed soil structure, maintenance of pore system, high SOM and associated aggregation and TN. On the other hand, the initial alteration of soil matrix and the distortion of pore space as well as loss of SOM could be reasons for the low SQI obtained from tilled treatments (Chi and CT). These results are in agreement with the findings of Sharma et al. (2008) in a study on soil management practices and soil quality indices in a semi-arid tropical Alfisol in India.

Regardless of tillage treatments, residue mulch treatment had slightly higher SQI than no mulch treatment although the difference was not significant (Figure 22). The statistical results of non-significant effect of both tillage and mulching on SQI can be as a resulted of other interlinked factors such as period of evaluation (relatively short for both tillage and residue mulch treatments), the single tillage application, influence of weather conditions, previous soil conditions before land preparation among others. Non-significant effect of tillage on SQI was also reported by Erkossa et al. (2007) and Sharma et al. (2008).

Considering the different soil layers, the SQI is generally low, which can be attributed to low fertility status of this soil or other soil variables not evaluated. The significantly highest SQI values from 0-10 cm layer is attributed to higher soil conditions of the surface layer (highest SOM, lowest BD, and highest TN) (Figure 23). This is expected because it is the superficial layer that receives manipulations such as soil mobilization, residue mulch, manure, etc. Also bulk of the root system and biological activity are confined to the surface layer.

The relative contribution of each limiting factor (bulk density, field capacity, pre-compression stress, organic matter and nutrient storage) to the overall SQI (Figure 24) of each treatment showed that a single SQ indicator irrespective of how is it measured and interpreted is not suitable for comparing overall soil quality status (TESFAHUNEGN, 2014). The highest contribution from water retention and permeation (combination of BD and FC) indicated the importance of good physical conditions for biological activity and nutrients cycling. Similarly, the high contribution from pre-compression stress shows its importance in soil compaction monitoring, an indication of soil internal strength. Interestingly, the low contribution of both SOM and TN, especially in the subsurface layers shows the critical state of the variables in this soil.

The significant positive correlation between the selected SQ indicators and management goals of sugarcane yield and soil water retention clearly showed that the selected minimum data set, BD, FC, σ_c, TN and SOM (Tables 19 and 20) are key indicators of soil quality which highly influenced the soil functions and overall soil quality of the sugarcane field. Likewise the correlation between sugarcane yield and SQI was positive (Table 21), although the low correlation was low and p-value was high, this may be due to the low SQI values or other factors that were not evaluated (ERKOSSA et al., 2007).

5.4 Temporal pattern of soil water status

The significantly lower mean SWS and higher log (Ψ) (Table 22) recorded in plots without residue mulch showed the importance of residue mulching on soil and water conservation which optimizes soil physical conditions affecting crop growth and yield. The effect of residue mulching on soli water storage has been discussed (see section 5.1.5). Soil matric potential is the energy required to remove a given amount of water from the soil matrix, and is a function of soil water content, soil texture and minerals as well as rainfall amount and distribution (Data not shown).

The higher coefficient of determination obtained when log (Ψ) was involved in the estimation of SWS showed the strong relationship between soil moisture and matric potential. According to Letey (1985), there exists a relationship between soil moisture and matric potential for a given soil, and thus it is possible to measure the matric potential and infer the soil moisture and vice versa if the appropriate relationship between them is established. Although the relationship is not linear (e.g, van GENUTCHEN, 1980), however, linear and multiple regressions were used in this study to be able to compare with other variables and also with the state-time equation which is normally expressed in linear form. The low coefficient of determination obtained using only the ET or P or their combination showed that the SWS could not be satisfactorily regressed from these parameters compared with that of log (Ψ).

The AC and CC lengths of 1, 2, 3, 4 and 5 lags indicated that these variables are autocorrelated or related with each other during no more than one, two, three, four and five consecutive sampling days (Table 23). Where both the AC and CC lengths are < 1 indicate that there was no correlation, especially that of P, indicating they are temporally independent and behave randomly (Nielsen and Wendroth 2003). The no autocorrelation obtained from P means observed rainfall amounts do not correlate with one another and are randomly distributed. This may be attributed to the erratic rainfall distribution observed during the season, being zero for certain periods and that it does not always give the same magnitude order throughout a given crop growing season due to some phenomenon such as the El Nino and La Nina oscillations of the south (KURUKULASURIYA and ROSENTHAL, 2013). These results are in consistence with the findings of Timm et al. (2011).

The unequal autocorrelation and crosscorrelation functions of the soil water storage in Table 23 is an evident that the temporal correlation structure of SWS measurements is not uniform for the different soil depths and management for different years. This behaviour can be attributed to the reason that SWS is seldom in equilibrium in the soil profile, as it is constantly being redistributed as a result of natural processes of rainfall, evaporation and infiltration at the soil surface (TIMM et al., 2006); extraction by plant roots and deep percolation as well as alterations and disruptions of soil structural state occasioned by human activities, including soil management practices (REICHERT et al. 2009). Thus, the autocorrelograms and crosscorrelograms of SWS and related properties are not expected to be unique (NIELSEN and WENDROTH, 2003) within a field due to spatial variation in soil properties, slope aspect, vegetal cover, and with time as a result of changing and shifting climatic conditions.

Since any of the SWS and Ψ can be used as the soil water status at any point in time, being related and be estimated from each other (LETEY, 1985), only SWS as an index of soil water status was used for the time series analysis. Thus, based on the autocorrelation of SWS, log (Ψ) and ET as well as the correlation between SWS and other variables, they showed the potential for explaining their contributions for estimating soil profile water storage using the state-time analysis (Table 24). The highest performance of the state-time model was recorded when SWS was estimated using only ET and P as explanatory variables when compared with the poor results of all classical regression models. Classical linear regression is based on the average values of each property throughout the time under evaluation, where the magnitudes of each attribute at a given time compared with their respective values at a previous or future time are neglected, whereas, the state-time analysis is not based on a mean value of a variable for the entire domain investigated, rather it considers the magnitude of a variable compared to its value at a nearby location or previous/future time. These results are in agreement with the findings of similar studies by Dourado-Neto et al. (1999) and Timm et al. (2003b, 2004, 2011). The state-time analysis also revealed that since an observation of a variable is an estimate of its true value, the analysis automatically considers that each measurement possesses an explicit observation as well as model error (denoted as ω_i) (NIELSEN and WENDROTH, 2003). In this study, the values of the errors, ω_i, had a mean of close to zero and were randomly distributed (Appendix III).

5.5 Temporal pattern of soil temperature

The different structure formation by tillage significantly ($p<0.05$) altered soil temperature. Heat flux in soils varied with soil composition, BD and water content, and is a function of soil heat capacity and thermal conductivity, both influencing the thermal diffusivity (DEC et al., 2009). The higher maximum, average soil temperature and amplitude of thermal wave obtained in the surface layers of all treatments is due to the radiant energy incidence before further propagation into soil profile and reflection, depending on surface condition. On the effect of tillage on soil temperature, the higher temperature observed in no-till treatments (NT and NTC) compared to tilled treatments (CT and Chi) is a function of soil BD, volumetric water content and particle-to-particle contact. Soil loosening by tillage destroys aggregate stability and heat flux through a changed surface roughness (POTTER et al., 1985). The increase in roughness in turns can change the area of soil surface which is open to the atmosphere and thus decreases heat conductivity and thermal diffusivity of the soil (ARSHAD and AZOOZ, 1996; NIDAL and REEDER, 2000). Further, lower soil bulk density implies that less water may be retained per unit volume of soil and more pore space is occupied by air. Since air is a good insulator with low thermal conductivity it contributes to low temperature in tilled treatments. On the other hand, under conditions of high BD, the contact between particles is increased, and consequently the soil thermal conductivity is increased (NIDAL and REEDER, 2000) and hence higher soil temperature (Tables 2 and 3). These results are in contrast to findings of Arshad and Azooz (1996) and Odjugo (2008), who reported higher temperatures in conventionally tilled soils compared to no-tillage treatment.

Irrespective of tillage method, the lower soil temperature in subsurface layers during the summer period is a function of higher soil water content. This finding is in agreement with that of Dec et al. (2009). In moist soils, heat capacity increases linearly with increasing water content; however, as water content increases, soil warming is hindered due to higher heat capacity because more energy is required for water evaporation than increasing soil temperature. During the winter period, soil is expected to be warmer than the overlying air, serving as a natural source for adding heat to the surrounding. However, the reverse was observed in this study as air temperature was still above that of the soil layers for most of the period (Figure 30). During this winter period, sugarcane was at late growth stage, with plant canopy entirely covering soil surface, thus shading soil from solar radiation and incidence energy. This modifies the temperature regime, especially the amplitude at the soil surface by reducing the maximum and increasing the minimum temperature at any depth, causing a small overall decrease in average soil temperature (HILLEL, 1998).

The initial effect of straw mulch application is the modification of soil temperature as a result of change in radiation balance. In this study, straw mulching suppressed mean soil surface temperature by 4.1 ^{o}C (Table 25). Oliveira et al. (2001) working on soil temperature in a sugarcane crop as a function of management system in Brazil found about 7 ^{o}C and therefore significantly higher surface temperature in no mulch treatment compared to mulched treatment. In a study by Odjugo (2008) on the effect of tillage systems and mulching on soil microclimate, growth and yield of yellow yam in Midwestern Nigeria, mean surface soil temperature was reduced by 4.4 ^{o}C by mulching. Olasantan (1999) observed a mean soil temperature difference of 2-7 ^{o}C between mulched and no mulch treatments. The mulch layer contains a significant amount of pore space and the majority of pore space is filled with air, which is a good insulator. Thus, air prevents energy conduction, indicating that straw mulch treatment had lower thermal conductivity than no mulch treatment. According to Walczak and Usowicz (1994), crop residue retention impacts soil thermal regimes due to the ability to reflect soil radiation, reduce evaporation and influence net heat exchange, temperature gradient and heat transfer. Liu et al. (2014) reported that, because straw mulch covering soil surface has higher albedo and lower thermal conductivity than the bare soil, it reduces the solar radiation reaching the soil and consequently reduces the soil temperature.

The essentially high suppression of maximum temperature by about 11 ^{o}C during the extreme summer soil thermal period in February (Table 25) shows that straw mulching could mitigate deleterious effects on roots and microbes, which extreme soil temperature could cause. Hu and Feng (2003) stated that higher temperature in bare soils promotes evaporation, reduces soil available water and accelerates microbial processes. The reduction in the mean and maximum soil temperature with depth could be a result of a relatively higher heat capacity caused by higher soil water content, especially in the 40-60 cm subsurface (Table 4).

During the critical winter period, the about 2-3 ^{o}C difference in average and maximum soil surface temperature between straw mulch and no mulch treatments was opposite to that obtained during the summer period, with mulch treatment > no mulch treatment (Table 25). Sharratt (2002) also observed near-surface temperature of about 2 ^{o}C in soils with stubble mulch than those without mulch. During the winter season, presence of straw mulch on soil surface insulates soil from colder air temperature, thus heat loss from soil is lower and soil temperatures are consequently higher than no straw mulch soil. The increase in soil temperature due to mulching could protect the soil from extreme thermal conditions that could make soil nutrients immobile and soil micro-organisms to be dormant (HU and FENG, 2003).

The range is an important parameter of semivariograms, indicating the separation distance by which an observation at a given time has influence over the observation at another time, or in other words the maximum distance up to which sampling locations are temporally autocorrelated. Those cases where average daily soil temperature experimental variograms were fitted to unbounded power or linear models indicated no sill, because the variance of observations within the time domain is not constant but keeps increasing. On the other hand, bounded semivariograms manifest constant variance throughout the time domain (NIELSEN and WENDROTH, 2003). The increase in temporal range with soil depth is an indication of stability and higher continuity of soil temperature over time in deeper layers, which shows that soil temperature especially in the 40-60 cm deeper layer would have higher temporal dependency compared to surface layer, depending on prevailing weather conditions. The differences obtained in magnitude of temporal range and sill variance between straw mulch and no mulch treatments showed that mulching influenced temporal covariance structure of soil temperature (Figure 32).

Comparing classical linear regression (Figure 31) and autoregressive state-time analyses (Figures 34 and 35) to estimate T_s from T_a for the 0-5 cm soil layer of the sugarcane field, an increased coefficient of determination from state-time analysis was observed, indicating better estimation potential than classical regression. Moreover, the higher transition coefficient of $T_{s_{t-1}}$ compared to $T_{a_{t-1}}$ is an indication that present value of soil temperature depends more on previous measurements of itself than previous observations of air temperature and vice-versa, if daily air temperature is the subject of research. These results of this study agreed with findings of a similar study by Dourado-Neto et al. (1999) on state-space analysis of soil water content and temperature in a sugarcane field. Likewise, Timm et al. (2011) working on temporal variability of soil water storage of an irrigated-coffee field found higher coefficients of determination in estimating soil water storage by state-time analysis in comparison to classical multiple regression. The state-time analysis also revealed that, since the observation of a variable is an estimate of its true value, the analysis automatically considers that each measurement possesses an explicit observation as well as model error (denoted as ω_t) (NIELSEN and WENDROTH, 2003). In this study, the values of the errors, ω_t, were randomly distributed, with mean close to zero (data not shown).

The consistency and reliability of the state-time approach by ignoring certain proportion of the T_s data was found following the gradual reduction of magnitude of the transition coefficient of T_s and coefficient of determination. The width of 95% confidence limit increased, because as more and more data are ignored variability increases (Figures 34(b & c) and 35 (b & c)). Timm et al. (2011) also reported similar findings when 50% and 75% of data were omitted during state-time analysis of soil water storage, evapotranspiration and precipitation in a coffee field in Brazil.

6 Tung-based cropping system

6.1 Rainfall distribution and potential evapotranspiration

The distribution of the daily rainfall (P) and atmospheric demand (potential evapotranspiration, ETp) during the 2012/2013 and 2013/2014 growing seasons of the tung-based cropping system is shown in Figure 36. Table 26 shows the total monthly and seasonal values of the P and ETp.

The total monthly P amounts ranged from 35 to 293 mm in 2012/2013 growing season, while the values were between 67 and 295 mm in 2012/2013 growing season, with the lowest amount of rainfall recorded during the winter months and the highest amount received during autumn and spring. The total seasonal rainfall amount received were 1550 and 1389 mm for the two growing seasons, respectively,

In 2012/2013 growing season, the total monthly values of ETp ranged between 4.7 and 151.8 mm, with the lowest atmospheric demand in the month of May and highest demand in January. During this growing season, the total monthly P values were lower than those of the ETp in the months of November, January and February. For the 2013/2014 growing season, the total monthly values of ETp ranged between 35 and 180 mm, with the lowest and highest atmospheric demand recorded in June and December, respectively. Likewise, the total monthly P amounts were lower than those of respective ETp values in September, October, December, January and February. The total ETp for each growing season was 968 and 1102 mm, respectively. Similarly, the total seasonal P was greater than the total seasonal atmospheric demand (Table 26).

Table 26. Total monthly rainfall and evaporativedemand of the atmosphere (potential evapotranspiration) during the 2012/2013 and 2012/2013 growing seasons of the tung-based cropping system at Santa Maria, southern Brazil.

	2012/2013		2013/2014	
	ETp	P	ETp	P
Months	---	mm	---	
May	5	124	-	-
Jun	15	35	35	81
Jul	19	70	46	114
Aug	57	75	64	164
Sep	64	178	93	67
Oct	90	255	124	109
Nov	146	73	146	295
Dec	149	293	180	93
Jan	152	145	161	132
Feb	105	98	139	109
Mar	101	189	113	227
Apr	71	140	82	105
Total	968	1550	1102	1389

ETp: potential evapotranspiration, mm; P: rainfall, mm.

6.2 Effect of cropping systems on soil quality indicators

6.2.1. Bulk density and porosity

The results of the initial and seasonal values of soil bulk density (BD) of the 0-10, 10-20 and 20-40 cm layers are presented in Table 27. Before the imposing of the crop rotation and intercropping systems in year 2012, the average values of BD among the different plots were approximately 1.50, 1.60 and 1.55 g/cm^3 for the 0-10, 10-20 and 20-40 cm layers, respectively, with an increase of BD values with depth and the highest BD value (1.61 g/cm^3) was obtained in the 10-20 cm layer. As expected, there was no significant difference ($p<0.05$) in the average BD values.

At harvest of 2012/2013 growing season, the average values of BD of the 0-10 cm surface layer was not significantly ($p<0.05$) differed among the different cropping systems, with the average values between 1.35 and 1.51 g/cm^3. For the 10-20 cm

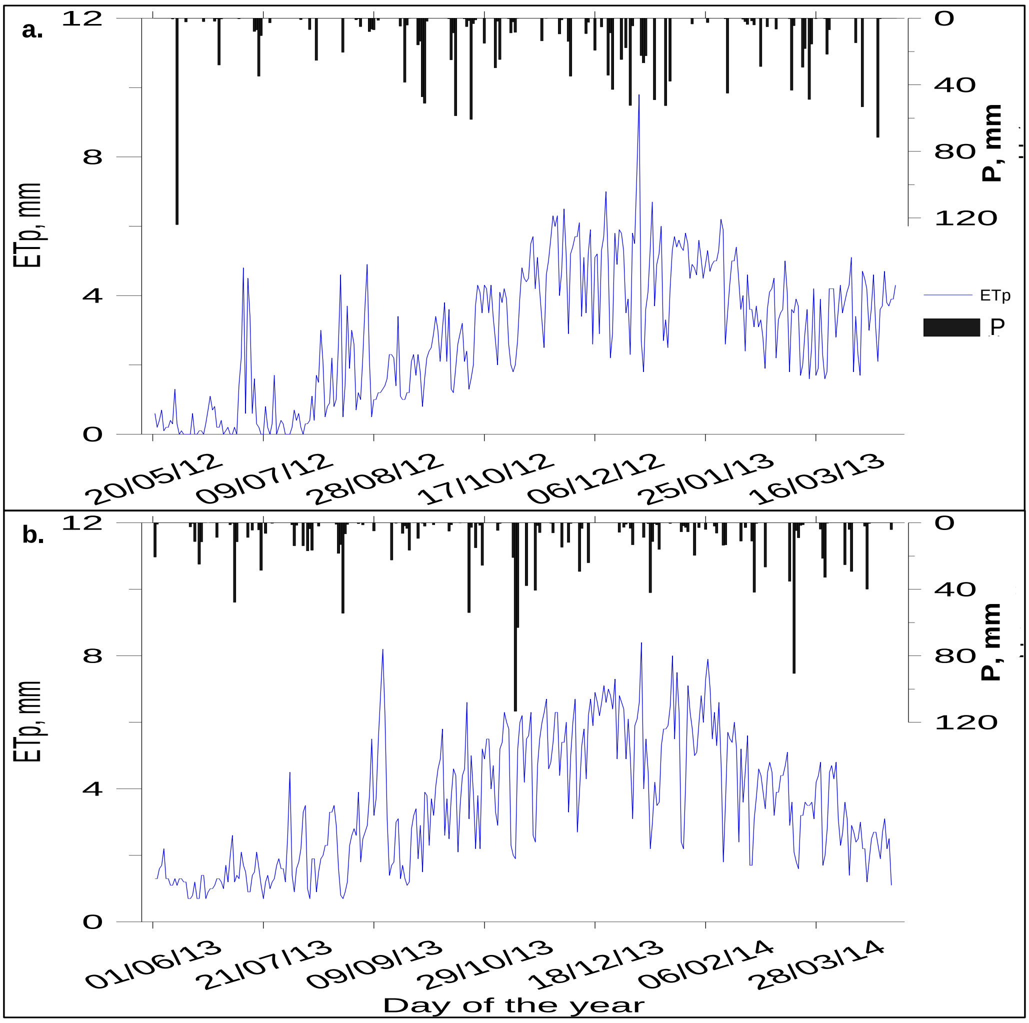


Figure 36. Temporal variability of rainfall and atmospheric demand (potential evapotranspiration) during the (a) 2012/2013 and (b) 2013/2014 growing seasons of the tung-based cropping system at Santa Maria, southern Brazil.

ET_p: environmental demand (potential evapotranspiration), mm

P: rainfall, mm

layer, the TOtP treatment had significantly highest value (1.68 g/cm^3) compared with other treatments, whereas for the 20-40 cm layer, average BD values ranged from 1.45 to 1.55 g/cm^3, with no significant difference among the treatments (Table 27).

At harvest of 2013/2014 growing season, cropping system did not significantly influence BD in all the soil layers. The average values of BD of the 0-10 cm

Table 27. Average values of soil bulk density (BD, g/cm^3) of the different soil layers and treatments of the tung-based cropping system at the beginning, in May 2012 and at harvest of 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

	---------------------------Treatments--------------------------				Average	LSD ($p<0.05$)
	TCS/So+I	TCS/So+O	TOtP	Control		
Soil depth, cm	2012 (Initial)					
0-10	1.50	1.49	1.57	1.50	1.52	3.03^{ns}
10-20	1.59	1.55	1.61	1.57	1.58	0.13^{ns}
20-40	1.56	1.58	1.52	1.53	1.55	0.52^{ns}
	2012/2013 growing season					
0-10	1.35	1.48	1.47	1.51	1.45	2.13^{ns}
10-20	1.61	1.64	1.68	1.58	1.63	4.03*
20-40	1.53	1.55	1.50	1.45	1.51	0.62^{ns}
	2013/2014 growing season					
0-10	1.40	1.49	1.46	1.55	1.47	0.88^{ns}
10-20	1.62	1.62	1.66	1.64	1.63	1.09^{ns}
20-40	1.53	1.50	1.49	1.51	1.51	0.16^{ns}

TCS/So+I: tung-crambe-sunflower/soybean + in-organic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean + organic fertilizer; TOtP: tung-oats-peanut; Control: sole tung.

*significant; and ns: not significant at 5% probability level by Fisher's least significant difference (LSD) test.

superficial layer were between 1.40 and 1.55 g/cm^3. In other layers, 10-20 and 20-40 cm, the average BD values ranged from 1.49 and 1.66 g/cm^3.

On the seasonal variability of BD, the overall average value of BD of the three soil layers evaluated did not change appreciably after each season (Table 27).

The average values and statistical results of the total porosity (Pt), macroporosity (Ma) and microporosity (Mi) are presented in Table 26. The total porosity (Pt) did not differ significantly ($p<0.05$) in all the soil before the application of cropping treatments in May 2012 (Table 28). Thus, the average values of Pt ranged between 0.35 and 0.39 cm^3 cm^{-3}. In general, the average values of Pt were lower in the sub-surface layers compared with the surface layer.

Table 28. Average values of total porosity, Pt, macroporosity, Ma, and microporosity, Mi, of the different soil layers and treatments of the tung-based cropping system at the beginning, in May 2012 and at harvest of 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

	Pt, cm^3 cm^{-3}			Ma, cm^3 cm^{-3}			Mi, cm^3 cm^{-3}		
	0-10	10 20	20-40	0-10	10 20	20-40	0-10	10 20	20-40
	--Soil depth, cm---								
Treatments	2010 (Initial)								
TCS/So+I	0.38	0.39	0.35	0.13	0.06	0.05	0.25	0.33	0.30
TCS/So+O	0.38	0.37	0.35	0.13	0.12	0.06	0.26	0.25	0.29
TOtP	0.36	0.34	0.36	0.09	0.08	0.06	0.27	0.26	0.29
Control	0.39	0.35	0.36	0.15	0.09	0.07	0.25	0.26	0.29
LSD($p<0.05$)	0.48^{ns}	0.41^{ns}	0.047^{ns}	1.01^{ns}	1.19^{ns}	0.12^{ns}	0.72^{ns}	1.46^{ns}	0.98^{ns}
	2012/2013 growing season								
TCS/So+I	0.44	0.33	0.35	0.19	0.08	0.07	0.25	0.25	0.28
TCS/So+O	0.40	0.33	0.35	0.13	0.08	0.08	0.27	0.25	0.27
TOtP	0.41	0.32	0.36	0.12	0.07	0.08	0.29	0.26	0.28
Control	0.39	0.36	0.38	0.12	0.11	0.09	0.27	0.25	0.29
LSD($p<0.05$)	0.90^{ns}	4.17*	0.82^{ns}	1.38^{ns}	3.45^{ns}	0.74^{ns}	2.37^{ns}	0.83^{ns}	0.94^{ns}
	2013/2014 growing season								
TCS/So+I	0.41	0.35	0.36	0.15	0.09	0.07	0.26	0.26	0.29
TCS/So+O	0.39	0.34	0.37	0.13	0.09	0.09	0.25	0.26	0.29
TOtP	0.39	0.32	0.36	0.13	0.06	0.09	0.26	0.26	0.27
Control	0.36	0.33	0.36	0.11	0.06	0.09	0.24	0.27	0.27
LSD($p<0.05$)	1.08^{ns}	2.70^{ns}	0.18^{ns}	0.49^{ns}	2.87^{ns}	1.52^{ns}	1.15^{ns}	0.29^{ns}	0.55^{ns}

TCS/So+I: tung-crambe-sunflower/soybean + in-organic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean + organic fertilizer; TOtP: tung-oats-peanut; Control: sole tung.

*significant; and ns: not significant at 5% probability level by Fisher's least significant difference (LSD) test.

At harvest of 2012/2013 growing season, the Pt was significantly ($p<0.05$) affected only in the 10-20 cm layer. The 0-10 cm superficial layer had average values of Pt between 0.39 and 0.44 cm^3 cm^{-3} among the cropping treatments. For other layers, the average Pt values ranged from 0.32 to 0.38 cm^3 cm^{-3}.

The evaluation done at harvest of 2013/2014 growing season also showed that the Pt was not significantly ($p<0.05$) influenced by different cropping systems. In the 0-10 cm surface layer, a comparison among the cropping treatments showed that average Pt was at par (about 0.40 cm^3 cm^{-3}).

A comparison of the seasonal variability of the Pt at the end of 2012/2013 growing season showed that the average values of Pt of the 0-10 cm superficial layer of TCS/So+O and TOtP treatments increased by 13% in each case, while there was no discernible trend in the average values of Pt in TCS/So+I and control treatments. At the end of 2013/2014 growing season, no discernible trend was obtained from TCS/So+O and TCS/So+I treatments and about 10% increase in the average values of Pt from TOtP treatment while the average Pt value from the control treatment decreased by about 10% (Table 28).

Macroporosity (Ma) did not differ significantly ($p<0.05$) in all the soil layers before the application of cropping treatments in May 2012 (Table 28). For the 0-10 cm surface layer, the average values of Ma ranged from 0.09 and 0.14 cm^3 cm^{-3}, however, the average values decreased in the sub-surface layers, with values ranging between 0.05 and 0.12 cm^3 cm^{-3}.

At harvest of 2012/2013 growing season, the Ma was not significantly ($p<0.05$) influenced in all the soil layers by cropping system. The 0-10 cm superficial layer had average values of Ma between 0.12 and 0.19 cm^3 cm^{-3}. For the 10-20 and 20-40 cm layers, the average Ma values ranged from 0.07 to 0.11 cm^3 cm^{-3}.

At harvest of 2013/2014 growing season, the Ma of all the soil layers did not differ significantly ($p<0.05$) among the different cropping systems. The 0-10 cm surface layer had average values of Ma ranging from 0.11 and 0.15 cm^3 cm^{-3}. For other subsurface layers, the Ma varied between 0.06 and 0.09 cm^3 cm^{-3}.

A comparison of the seasonal variability of the Ma between 2012 (initial) and at harvest of 2012/2013 growing season showed an increase of 40 and 28% from the 0-10 cm superficial layer of TCS/So+I and TOtP treatments respectively, no discernible increase from TCS/So+O treatment while the average value decreased by about 16% in the control treatment. Likewise, an increase of about 10, 8 and 39% in Ma values of the 0-10 cm superficial layer were recorded from TCS/So+I, TCS/So+) and TOtP treatments at the end of 2013/2014 growing season. However, the average Ma value in the control treatment decreased by about 20% during the same period (Table 28).

Microporosity was not significantly ($p<0.05$) influenced by intercropping and crop rotation systems in both seasons and all the soil depths (Table 28). At initial, the average values of Mi ranged between 0.25 and 0.27 cm^3 cm^{-3} in the 0-10 cm surface layer, while it slightly increased with soil depth, up to 0.33 cm^3 cm^{-3}. At harvest of both 2012/2013 and

2013/2014 growing seasons, the average values of Mi varied slightly in the 0-10 cm surface layer while it was relatively stable in the sub-surface layers.

6.2.2 Field capacity, permanent wilting point and maximum available water

The distribution of average soil volumetric water content at field capacity (FC), and permanent wilting point (PWP) for the 0-10, 10-20 and 20-40 cm soil layers and treatments of the tung-based crop rotation and intercropping systems before imposing the cropping treatments in May 2012 and at harvest of 2012/2013 and 2013/2014 growing seasons is shown in Figures 37a, b and c, respectively. Table 29 shows the maximum available water capacity (AW) for the 0-40 cm profile.

At the beginning of the experiment in 2012, the average values of the FC of the different soil layers of the profile varied between 0.23 and 0.28 cm^3 cm^{-3}, and these average values did not differ significantly. Irrespective of the plots, the pooled FC values were 0.24, 0.25 and 0.28 cm^3 cm^{-3} for the 0-10, 10-20 and 20-40 cm layers, respectively. At harvest of both 2012/2013 and 2013/2014, the average values of the FC of the different soil layers also ranged from 0.23 to 0.28 cm^3 cm^{-3}, with no significant differences among the treatments. Similarly, the PWP did not significantly ($p<0.05$) differ at initial and by cropping systems during both growing seasons. The average values of the PWP of the different soil layers of the profile varied between 0.08 and 0.11 cm^3 cm^{-3}, and irrespective of the tung plots, the pooled values being 0.08, 0.09 and 0.11 cm^3 cm^{-3} for the 0-10, 10-20 and 20-40 cm layers, respectively, indicating increase with soil depth. At the end of the 2012/2013 growing season, the PWP had average values between 0.08 and 0.12 cm^3 cm^{-3}, however at 2013/2014 harvest, the average values ranged from 0.09 to 0.14 cm^3 cm^{-3} (Figure 37).

The maximum available water capacity (AWmax) for root growth was not significantly ($p<0.05$) at the onset and by cropping systems in all cases. The average values of AWmax of the 0-10, 10-20 and 20-40 cm soil layers were almost at par, with no discernible trend for all treatments and both growing seasons (Table 29). For the 0-40 cm total profile AWmax, the average values were varied between 57 and 66 mm at initial and end of both 2012/2013 and 2013/2014 growing seasons (Table 29).

Table 29. Average values of maximum soil available water, AWmax (mm), per layer and total soil profile available water capacity of the tung-based cropping system before imposing the cropping treatments in May 2012 and at harvest of 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

	------------------------Treatments------------------------				
	TCS/So+I	TCS/So+O	TOtP	Control	LSD($p<0.05$)
Soil depth, cm	2012 (Initial)				
0-10	15	16	17	15	1.19^{ns}
10-20	16	15	15	15	0.97^{ns}
20-40	35	33	34	33	0.16^{ns}
Total (0-40)	67	64	66	63	2.45^{ns}
	2012/2013 growing season				
0-10	15	15	17	16	1.68^{ns}
10-20	14	13	14	15	0.32^{ns}
20-40	30	31	32	31	0.36^{ns}
Total (0-40)	59	60	63	62	2.67^{ns}
	2013/2014 growing season				
0-10	16	16	16	15	0.37^{ns}
10-20	14	15	15	17	2.56^{ns}
20-40	27	32	27	29	2.34^{ns}
Total (0-40)	57	63	58	60	2.13^{ns}

TCS/So+I: tung-crambe-sunflower/soybean + in-organic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean + organic fertilizer; TOtP: tung-oats-peanut; Control: sole tung.

*significant; and ns: not significant at 5% probability level by Fisher's least significant difference (LSD) test.

6.3 Soil saturated hydraulic conductivity

The seasonal variation of average saturated soil hydraulic conductivity, Ksat, for the 0-10, 10-20 and 20-40 cm soil layers of the tung field under different cropping systems at initial (2012) and end of 2012/2013 and 2013/2014 growing seasons is shown in Figure 38. The Ksat was not significantly ($p<0.05$) affected by cropping system.

At the beginning of the experiment in 2012, average values of Ksat ranged between 136 and 159 mm/hr in the 0-10 cm surface layer, from 64 to 77 mm/hr in the 10-20 cm layer and from 12 to 22 mm/hr in the 20-40 cm deeper layer. At harvest of 2012/2013 growing

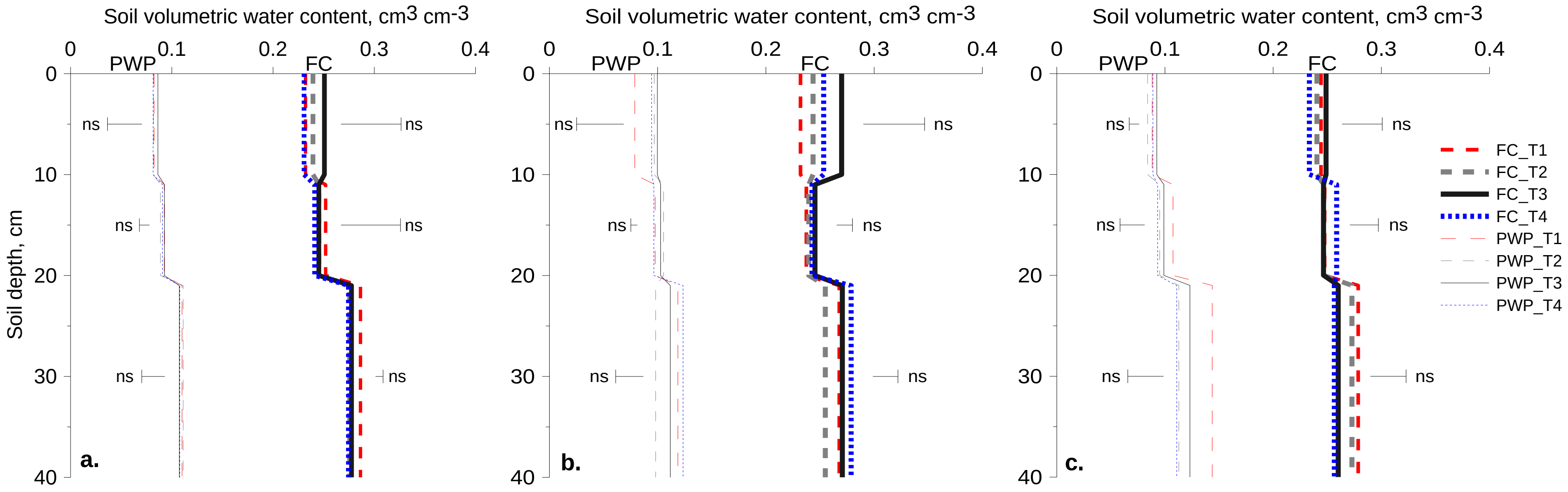


Figure 37. Distribution of field capacity (FC, cm^3 cm^{-3}) and permanent wilting point (PWP, cm^3 cm^{-3}) of the 0-40 cm soil profile and between different treatments of the tung-based cropping system at the beginning, (a) May 2012 and at harvest of (b) 2012/2013 and (c) 2013/2014 growing seasons at Santa Maria, southern Brazil.

T1: tung-crambe-sunflower/soybean rotation + in-organic fertilizer (TCS/So+I); T2: tung-crambe-sunflower/soybean rotation + organic fertilizer (TCS/So+O); T3: tung-oats-peanut rotation (TOtP); T4: sole tung (control).

Horizontal half-bars are the mean significant difference values at 5% level of probability by Fisher's LSD-test; *significant; ns: not significant season, average Ksat values increased in the 0-10 cm surface layer of TCS/So+I, and TOtP treatments by about 7 and 15%, respectively, no discernible change from TCS/So+O treatment while a decrease of about 5% was recorded from the control treatment compared with initial values. At the end of 2013/2014 growing season, there was no appreciable change in Ksat for all the treatments in comparison with previous season (2012/2013 season).

For the 10-20 and 20-40 cm layers, average Ksat values either decreased or increased at the end of each growing season with respect to previous values in each case.

6.4 Soil organic matter, total nitrogen, carbon pool and C/N ratio

The results of average values and statistical comparison of total soil organic matter (SOM), total nitrogen (TN), soil organic carbon to nitrogen (C/N) ratio, and carbon pool (Cpool) are presented in Table 30. There was no significant difference ($p<0.05$) in the statistical comparison of the soil organic matter and nutrient variables at the beginning of the experiment in year 2012 as well as at harvest of both 2012/2013 and 2013/2014 growing seasons.

In year 2012, the average values of TN were at par for all the treatments in both the 0-10 cm (1.0 g/kg) and 10-20 cm (0.73 g/kg) layers. At the end of 2012/2013 growing season, average TN values remained at 1.0 g/kg in TCS/So+I, TCS/So+O and TOtP treatments whereas it slightly decreased to 0.93 g/kg in control treatment. At harvest of 2013/2014 season, average values of TN slightly increased to 1.06, 1.28 and 1.23 g/kg in TCS/So+I, TCS/So+O and TOtP treatments, respectively while the average value in control treatment remained unchanged. For the 10-20 cm layer, average values of TN ranged between 0.66 and 0.72 g/kg at the end of harvest in 2012/2013 growing season. At the end of 2013/2014 season, average TN values were between 0.70 and 0.84 g/kg (Table 30).

The average values of SOM of the 0-10 and 10-20 cm layers of the tung field were about 2.0 and 1.5%, respectively in all the four plots in May 2012. At the end of 2012/2013 growing season, average SOM content remained nearly unchanged in TCS/So+I, TCS/So+O and TOtP treatments and decreased by about 10% in control treatment. However, at harvest of 2013/2014 season, average values of SOM had increased by about 19% in TCS/So+O and TOtP

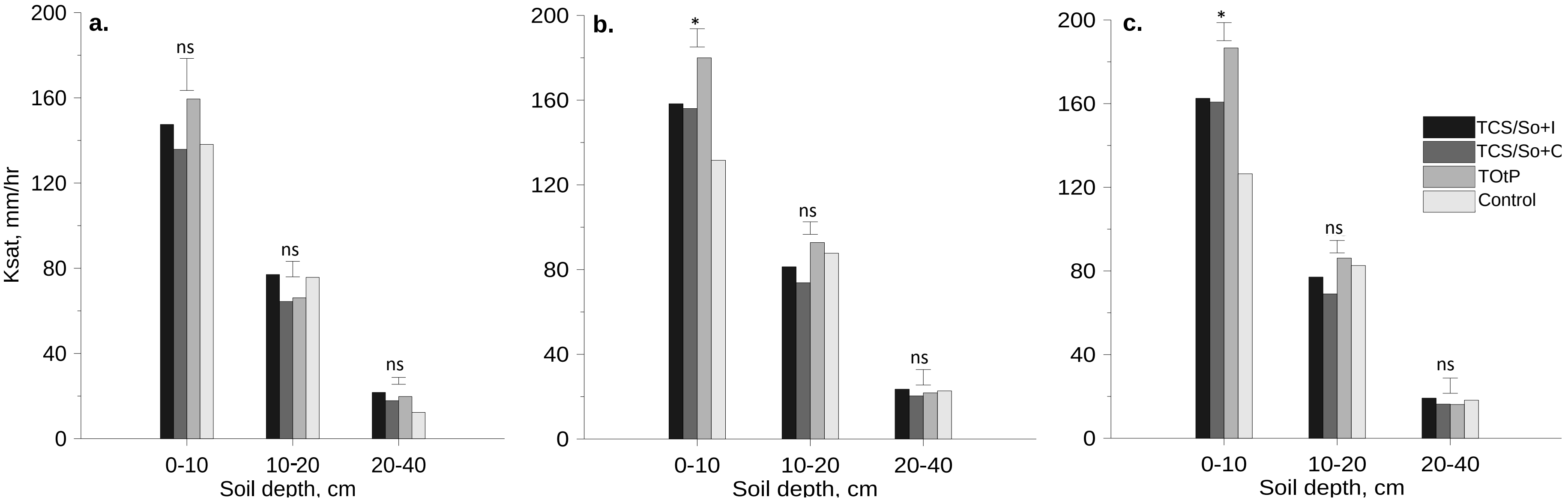


Figure 38. Average values of Ksat, mm/hr in the 0-10, 10-20 and 20-40 cm soil layers and between different treatments of the tung-based cropping system at the beginning, (a) May 2012 and at harvest of (b) 2012/2013 and (c) 2013/2014 growing seasons at Santa Maria, southern Brazil.

TCS/So+I: tung-crambe-sunflower/soybean + in-organic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean + organic fertilizer; TOtP: tung-oats-peanut; Control: sole tung.

The horizontal bars are the mean significant difference values at 5% level of probability by Fisher's LSD-test

Table 30. Average values of total nitrogen (TN) and soil organic matter (SOM), carbon/nitrogen ratio (C/N), and soil organic carbon pool (Cpool) of the 0-10 and 10-20 cm soil layers of the different treatments of the tung-based cropping system at the beginning, in May 2012 and at harvest of 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

	------------------2012 (Initial)-----------------				---------2012/2013 growing season----------				-----------2013/2014 growing season--------			
	TN g/kg	OM %	C/N -	Cpool Mg/ha	TN g/kg	OM %	C/N -	Cpool Mg/ha	TN g/kg	OM %	C/N -	Cpool Mg/ha
Treatments						0-10 cm						
TCS/So+I	1.04	2.10	11.7	18.4	1.04	2.03	11.3	16.0	1.04	1.94	10.8	15.7
TCS/So+O	1.02	2.04	11.6	17.7	1.03	1.97	11.1	17.0	1.28	2.42	11.0	20.8
TOtP	0.97	1.94	11.6	17.7	1.00	1.92	11.1	16.4	1.23	2.30	10.8	19.8
Control	1.01	1.98	11.4	17.2	0.93	1.79	11.1	15.6	0.93	1.70	10.6	15.2
LSD ($p<0.05$)	0.45^{ns}	0.65^{ns}	2.10^{ns}	0.15^{ns}	0.73^{ns}	0.76^{ns}	1.04^{ns}	0.20^{ns}	2.51^{ns}	2.80^{ns}	0.90^{ns}	1.82^{ns}
						10-20 cm						
TCS/So+I	0.73	1.49	11.9	13.8	0.72	1.43	11.5	13.4	0.84	1.62	11.2	14.9
TCS/So+O	0.73	1.50	11.9	13.4	0.68	1.36	11.7	12.9	0.74	1.41	11.1	13.2
TOtP	0.75	1.50	11.6	14.0	0.68	1.36	11.6	13.3	0.70	1.32	10.9	12.7
Control	0.71	1.39	11.4	12.7	0.66	1.34	11.8	12.3	0.75	1.40	10.8	13.3
LSD ($p<0.05$)	0.16^{ns}	0.49^{ns}	1.09^{ns}	0.45^{ns}	0.33^{ns}	0.14^{ns}	0.92^{ns}	0.25^{ns}	1.03^{ns}	0.94^{ns}	0.39^{ns}	0.67^{ns}

TCS/So+I: tung-crambe-sunflower/soybean + in-organic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean + organic fertilizer; TOtP: tung-oats-peanut; Control: sole tung.

*significant; ns: not significant. LSD: Fisher's Least significant difference test at 5% level of probability treatments and decreased by about 8 and 14% in TCS/So+I and control treatments, respectively. The average values of SOM also decreased slightly in the 10-20 cm soil layer compared with the surface layer, with the average values ranging from 1.34 to 1.43% at the end of 2012/2013 growing season and between 1.32 and 1.62% in 2013/2014 growing season.

The average values of the C/N ratio from the different cropping systems was not more than 12 at the beginning and end of two consecutive growing seasons (Table 30). The average value of Cpool of the 0-10 cm layer was about 18 Mg/ha in 2012, which slightly decreased to about 16 Mg/ha in all treatment at harvest of 2012/2013 season. At harvest of 2013/2014 season, the average Cpool values increased to about 20 Mg/ha in TCS/So+O and TOtP treatments while it decreased to 15 Mg/ha in control treatment. In the 10-20 cm layer, the average values Cpool did not significantly differ among the treatments and between seasons, with values ranging between 12.3 and 14.9 Mg/ha (Table 30).

6.5 Degree of compaction

The seasonal changes in the estimated values of degree of compaction (DC) of the different soil layers and treatments of the tung-based agroforestry system are presented in Table 31. Cropping system did not significantly ($p<0.05$) influence DC for all soil depths and growing seasons evaluated. Before the imposition of intercropping treatments in 2012, the average values of DC of the 0-10 cm surface layer varied between 82 and 86%. At harvest of 2012/2013 growing season, average DC values decreased, ranging between 74 and 83%, For the 2013/2014 growing season, the estimated DC values ranged from 76 to 85%. On seasonal basis, the average values of DC were at par.

For the 10-20 and 20-40 cm layers, higher values of DC were obtained, which ranged between 82 and 92%, at initial and end of each growing season evaluated. In all, the average DC values were less than 90%, except in the 10-20 cm soil layer of TOtP and control treatments where the DC reached about 90% (Table 31).

Table 31. Average values and statistical comparison of degree of compaction, DC (%) of the 0-10, 10-20 and 20-40 cm layers of the tung field at initial (2012) and at harvest of2012/2013 and 2013/2014 growing seasons at Santa Maria, Brazil.

	-----------------------Treatments----------------------				
Soil	TCS/So+I	TCS/So+O	TOtP	Control	LSD ($p<0.05$)
depth, cm	2012 (Initial)				
0-10	82	82	86	82	0.76^{ns}
10 20	87	85	88	86	1.02^{ns}
20-40	86	87	84	84	0.89^{ns}
	2012/2013 growing season				
0-10	74	81	80	83	2.87^{ns}
10 20	88	90	92	87	1.11^{ns}
20-40	84	85	82	80	1.56^{ns}
	2013/2014 growing season				
0-10	77	82	80	85	2.09^{ns}
10 20	89	89	91	90	0.65^{ns}
20-40	84	82	82	83	0.63^{ns}

TCS/So+I: tung-crambe-sunflower/soybean + in-organic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean + organic fertilizer; TOtP: tung-oats-peanut; Control: sole tung.
ns: not significant at 5% level of probability by Fisher`s LSD test

6.6 Soil water retention (SWR)

The temporal variability of average daily soil water retention (mm) of the 0-80 cm profile near tung and within the intercrop rows during the two consecutive winter periods, June to October of 2012 and 2013, respectively; and two consecutive summer periods, November to April of 2012/2013 and 2013/2014, respectively are presented in Figures 39 and 40, respectively.

At about two weeks, after planting intercrops in 2012 (01/06/2012), the average values of soil water retention (SWR) in the 0-80 cm soil layer closed to tung plant varied slightly, from 209 to 214 mm, which did not significantly ($p<0.05$) differ among the cropping treatments. At developmental stage of the intercrops (04/07/2012), the average SWR values increased, ranging between 219 and 221 mm, also not significantly differ among the cropping

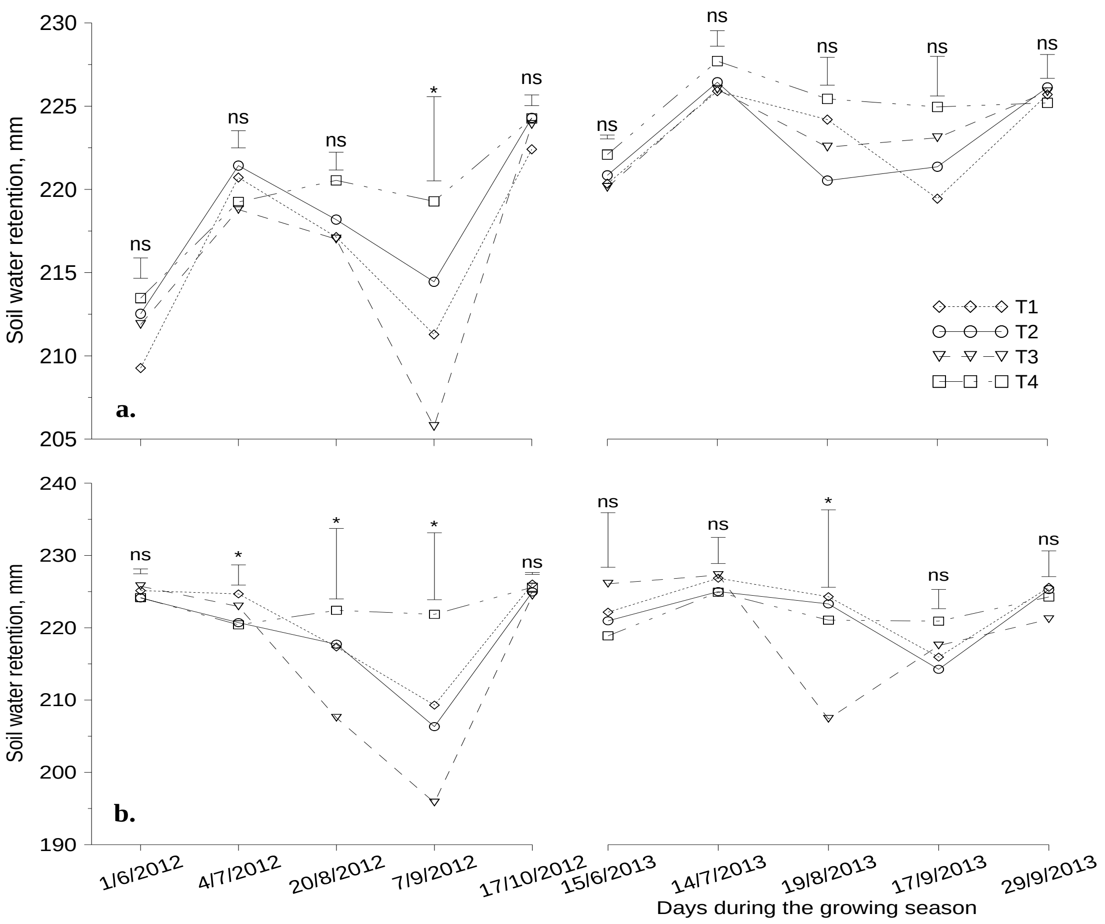
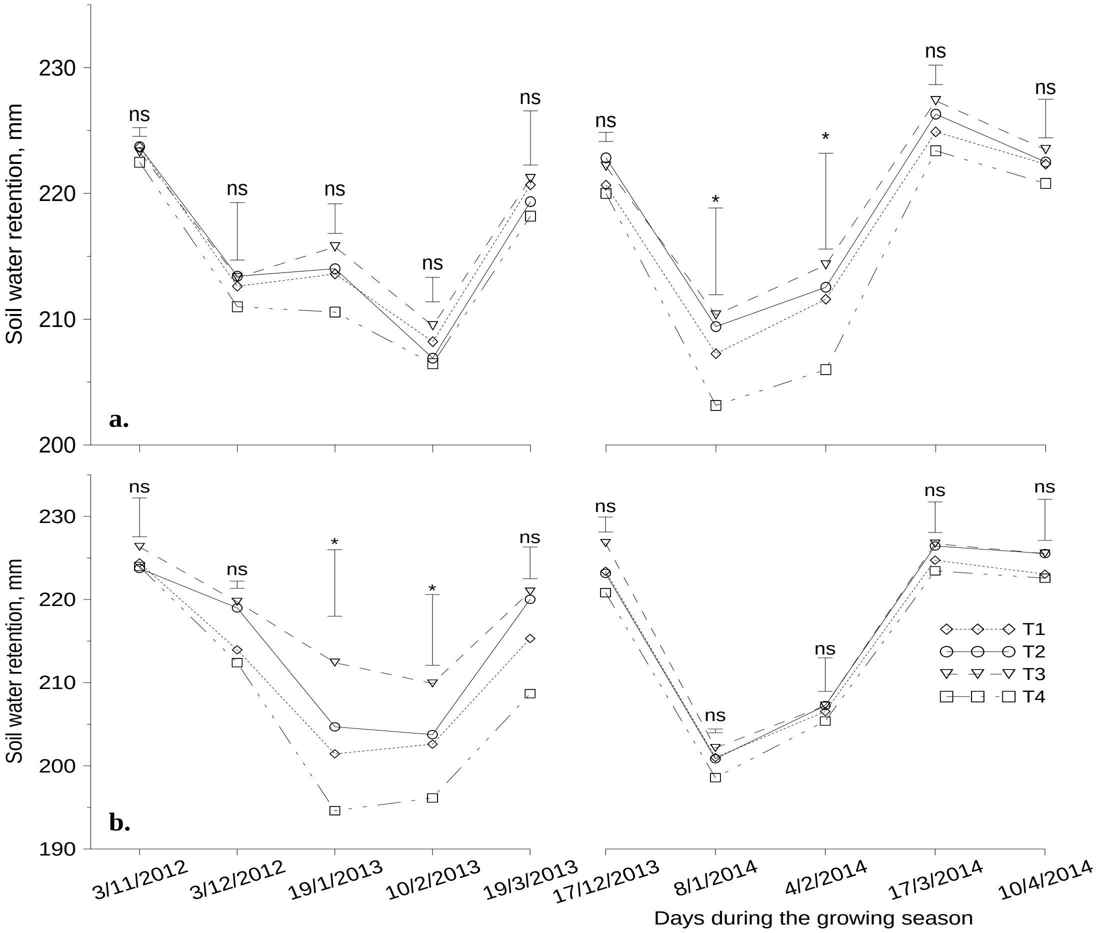


Figure 39. Temporal variability of average daily soil water retention (mm) of the 0-80 cm profile (a) close to tung plant and (b) within intercrop during winter period of 2012/2013 and 2013/2014 growing seasons at Santa Maria, Brazil.

TCS/So+I: tung-crambe-sunflower/soybean + in-organic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean + organic fertilizer; TOtP: tung-oats-peanut; Control: sole tung.

ns: not significant at 5% level of probability by Fisher's Least square difference (LSD) test.

systems. During the mid- and late season growth stages of the intercrops, the average SWR values decreased and was significantly highest (about 220 mm) at late season in from control treatment compared with other treatments. At harvest in October of 2012, the average values of SWR were at par, about 223 mm, for all the treatments. During the winter of 2013, the same trend in the average values of SWR was observed, with the cropping treatments having no significant effect on average SWR, however the average soil profile water retention was slightly higher compared with that of 2012 winter period (Figure 39a). Within the intercrops, the average values of soil water retention (SWR) of the0-80 cm soil layer was about 225 mm



Fgure 40. Temporal variability of average daily soil water retention (mm) of the 0-80 cm profile (a) close to tung plant and (b) within intercrop during summer period of 2012/2013 and 2013/2014 growing seasons at Santa Maria, Brazil.

TCS/So+I: tung-crambe-sunflower/soybean + in-organic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean + organic fertilizer; TOtP: tung-oats-peanut; Control: sole tung.

ns: not significant at 5% level of probability by Fisher's Least square difference (LSD) test.

at two weeks after planting intercrops in 2012 (01/06/2012), or at the initial growth stage of the intercrops. At crop developmental stage (04/07/2012), average SWR values ranged between 220 and 225 mm, with significantly highest value from TCS/So+I treatment. During the mid- and late season stages of the intercrops (28/8-17/9/2012), average SWR value was significantly highest (about 222 mm) in the control treatment compared with other treatments. At harvest, average values of SWR were at par, about 225 mm, for all the treatments. In the winter period of 2013, there was no significant variability in the SWR measured very closed to the tung plant among the different treatments, with a more or less similar trend compared with those of 2012 winter period (Figure 39b). A comparison of seasonal variation of SWR showed higher temporal variability in 2012 than 2013. For the summer period, different behaviour in soil water dynamics was observed. On 3rd November 2012, a day after planting of peanut and sunflower (intercrops), the average value of SWR, measured very close to tung plant, was lowest in the control treatment (222.4 mm) and at par (about 224 mm) in other treatments. In December 2012 and January and February 2013, the average SWR values decreased, as low as 206.5 mm from the control treatment on one of the hottest days in February. On 19/3/2013, when the intercrops have reached maturity stage, the average values of SWR increased, and remained unchanged till harvest. For the 2013/2014 summer period, similar trend was observed, but lower value of SWR was observed during the month of January 2014 compared with that of previous summer season.

In most of the summer period, lowest values of SWR were obtained from the control treatment and the effect was significant during the hot months of January and February 2014 (Figure 40a).

Within the intercrops, the average values of SWR in the 0-80 cm layer at planting (3rd November, 2012) were almost at par (about 226 mm), with no difference between the plots. At crop developmental stage in December 2012, the average SWR values did not significantly differ among the different cropping treatments, however they decreased, with values ranging between 212 and 220 mm. Further significant reduction in SWR was obtained in the months of January and February 2013, with average SWR value as low as 195 mm from the control treatment. In March, the average SWR increased and no appreciable change was observed till harvest in April (Figure 40b). For 2013/2014 summer period, the initial average SWR value was also highest (227 mm) in TOtP treatment compared with other treatments and a similar decrease in average SWR values was observed in the hot months of January and February 2014, which was as low as 199 mm in January. There was no discernible change in soil water storage for all the treatments between March and April. In this season, cropping system had no significant ($p<0.05$) influence on average soil profile water retention. A comparison of seasonal variation of SWR showed a more pronounced temporal variability in 2014 than 2013 (Figure 40b).

6.7 Tung plant height

The average values of tung plant height at the beginning, in May 2012 and at harvest of 2012/2013 and 2013/2014 growing seasons are presented in Figure 41. Cropping system did not significantly ($p<0.05$) influence tung plant height at harvest of the two consecutive growing seasons. Before the application of cropping systems in May 2012, the average height of the young tung plant was at about 1.4 m. At harvest of 2012/2013 growing season, the average plant values increased, ranging from 2.6 to 2.8 m, although the control treatment appeared to have the lowest height. At the end of 2013/2014 growing season, tung plant height also increased, as high as 4.2 m in TCS/So+I treatment and the control treatment also having the lowest value (3.9 m). The average values of the relatively seasonal growth rate were 102, 81, 97 and 89% for TCS/So+I, TCS/So+O, TOtP and control treatments, respectively after harvest of 2012/2013 season compared with the initial height and increase of 48, 43, 44 and 34% from TCS/So+I, TCS/So+O, TOtP and control treatments, respectively at the end of 2013/2014 season compared with previous season. The total growth rate over the two consecutive growing seasons showed that tung plant height had increased by 199, 158 and 185% as a result of the different cropping system and soil amendment, TCS/So+I, TCS/So+O and TOtP treatments, respectively compared to 154% increase in plant height recorded from sole tung, the control treatment.

6.8 Soil quality assessment

6.8.1 Minimum data set (MDS)

The rotated factor loadings, communalities, eigenvalues, proportion of the total variance explained by each principal component (PC) and cumulative variance of the principal component factors of the 0-10 and 10-20 cm soil layers of the tung-based cropping system at initial (May 2012) and at the end of 2012/2013and 2013/2014 growing seasons are presented in Tables 32 and 33.

In 2012 (initial), the PCA of the 0-10 cm surface layer had PC1 (see Table 32) with

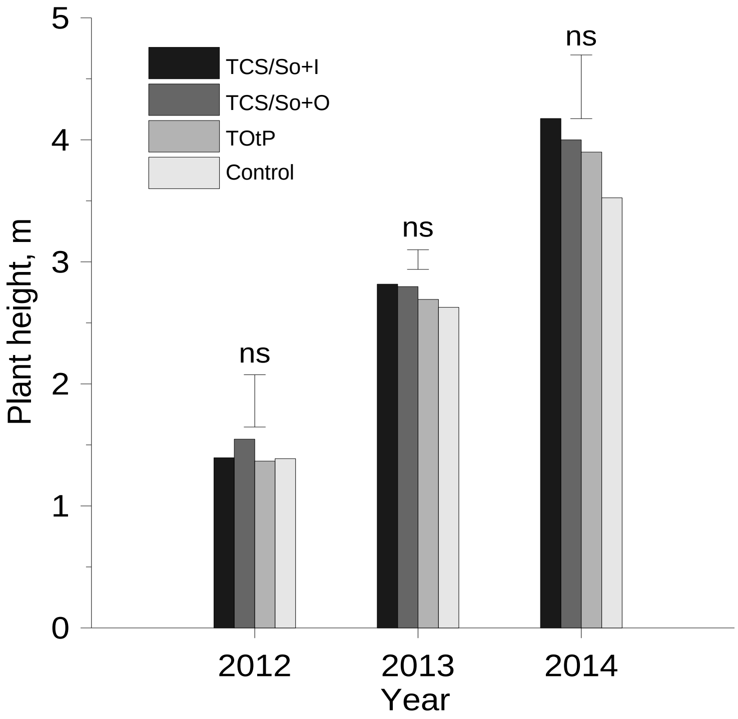


Figure 41. Average values of tung plant height at the beginning, in May 2012 and at harvest of different crop rotation and intercropping systems of 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

TCS/So+I: tung-crambe-sunflower/soybean rotation + inorganic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean rotation + organic fertilizer; TOtP: tung-oats-peanut rotation; Control: sole tung. ns: not significant at 5% level of probability by Fisher's Least square difference (LSD) test.

BD, Pt, and Ma as variables with high loading rates, and was designated as water retention and permeation factor. Ma was selected because of highest loading rate while the BD was retained for further analysis because of its importance and effect on soil pore space. For PC2, TN, SOM and Cpool had highest loading rates, and were designated as organic matter and nutrient storage factor. TN was retained to represent nutrient cycling while SOM was retained for organic matter because of its higher loading rate compared with Cpool. PC3 had Mi and AW with high loading rates, Mi was dropped because it is related to PC1 and AW was retained for its importance. Thus, Ma, BD, TN, SOM and AW were retained as MDS for the initial period, 2012.

Table 32. Rotated factor loadings and communalities of the management soil quality indicators of the 0-10 cm surface layer of the tung-based cropping system at initial (May 2012) and after each of the 2012/2013and 2013/2014 growing seasons at Santa Maria, southern Brazil.

	2012				2012/2013				2013/2014				
Soil	--------------PC-------------				--------------PC-------------				---------------------PC------------------				
Par.	1	2	3	Com	1	2	3	Com	1	2	3	4	Com
Ksat	-.741	.162	-.035	.577	-.103	.650	-.144	.453	.490	-.444	-.066	-.280	.520
BD	.894	.364	-.135	.950	-.985	-.091	-.023	.979	-.971	-.042	-.158	.061	.973
Pt	-.908	-.278	.149	.924	.946	.175	.177	.956	.950	.151	.202	-.042	.968
Ma	-.941	-.287	-.066	.971	.820	.096	-.401	.842	.938	.077	-.261	-.061	.958
Mi	.781	.236	.535	.952	.227	.123	.865	.814	.005	.154	.980	.043	.986
FC	.779	.300	.494	.940	-.450	.304	.795	.926	-.103	.261	.957	.020	.994
PWP	.534	.736	.026	.828	-.720	.572	.196	.884	-.453	.385	.272	.616	.808
AW	.680	-.108	.650	.896	.006	-.079	.937	.884	.224	-.006	.824	-.434	.917
TN	-.009	.971	.166	.970	.326	.905	.212	.970	.171	.956	.155	-.036	.968
SOM	.016	.980	-.032	.963	.279	.897	.299	.972	.175	.950	.177	-.147	.985
CN	-.132	.073	.866	.773	.192	-.232	-.751	.654	.006	-.260	-.241	.792	.752
Cpool	.512	.845	.047	.978	-.082	.951	.210	.956	-.108	.972	.086	.000	.963
Eigen	6.76	2.46	1.51		4.53	3.65	2.11		4.17	3.49	2.11	1.02	
Var, %	56.32	20.48	12.55		37.73	30.42	17.61		34.77	29.08	17.55	8.54	
Cum, %	56.32	76.80	89.35		37.73	68.15	85.75		34.77	63.85	81.39	89.93	

Soil Par: soil parameters; PC: principal component; Com: communality values; Ksat: soil saturated hydraulic conductivity, mm/hr; OM: organic matter, %; Cpool: soil organic carbon density, Mg/ha; TN: total nitrogen, g/kg; C/N: carbon to nitrogen ratio; BD: soil bulk density, g/cm^3; Pt: total porosity, cm^3 cm^{-3}; Ma: macroporosity, cm^3 cm^{-3}; Mi: microporosity, cm^3 cm^{-3}; FC: field capacity, cm^3 cm^{-3}; PWP: permanent wilting point, cm^3 cm^{-3}; AW: available water capacity, mm.

Eigen: eigenvalues; Var.: variance explained by each parameter, %; Cum: cumulative variance explained.

*Values in bold in each PC column were used to select the minimum data set (MDS)

Table 33. Rotated factor loadings and communalities of the management soil quality indicators of the 10-20 cm layer of the tung-based cropping system at initial (May 2012) and after each of the 2012/2013and 2013/2014 growing seasons at Santa Maria, southern Brazil.

	2012					2012/2013					2013/2014			
Soil	PC					PC					PC			
Par.	1	2	3	4	Com	1	2	3	4	Com	1	2	3	Com
Ksat	.326	.111	-.232	.650	.595	-.101	-.124	-.006	-.955	.937	-.546	.232	.625	.743
BD	-.476	-.001	-.855	-.028	.959	.093	-.874	.034	-.049	.776	.431	-.734	-.344	.843
Pt	.799	.003	.588	.084	.991	-.006	.949	-.008	.122	.916	-.086	.882	.193	.822
Ma	-.098	-.109	.981	.057	.987	-.254	.862	-.392	-.006	.962	-.623	.702	-.103	.892
Mi	.985	.082	-.027	.056	.981	.509	-.199	.787	.213	.963	.894	-.081	.392	.959
FC	.975	.121	.076	.087	.978	.445	-.245	.777	.285	.942	.929	-.164	.273	.964
PWP	-.072	.903	-.192	.007	.858	.745	-.469	-.124	.294	.876	.799	.367	-.189	.809
AW	.985	-.026	.110	.030	.984	-.393	.279	.813	-.060	.897	.411	-.604	.565	.852
TN	.174	.943	.140	.205	.981	.979	.050	.053	.064	.968	.700	.684	-.050	.961
SOM	.202	.944	.050	-.160	.960	.945	-.025	.290	-.042	.979	.809	.467	-.100	.882
CN	-.077	-.011	.239	.883	.843	-.076	.295	-.772	.352	.814	-.183	.821	.166	.735
Cpool	-.202	.768	-.555	.174	.968	.948	-.209	.047	.045	.946	.807	.532	-.120	.949
Eigen	4.56	3.53	1.74	1.25		5.28	2.46	2.17	1.07		5.18	4.04	1.19	
Var, %	37.98	29.45	14.53	10.41		43.99	20.52	18.08	8.88		43.15	33.65	9.95	
Cum, %	37.98	67.43	81.97	92.38		43.99	64.51	82.59	91.47		43.15	76.81	86.76	

Soil Par: soil parameters; PC: principal component; Com: communality values; Ksat: soil saturated hydraulic conductivity, mm/hr; OM: organic matter, %; Cpool: soil organic carbon density, Mg/ha; TN: total nitrogen, g/kg; C/N: carbon to nitrogen ratio; BD: soil bulk density, g/cm^3; Pt: total porosity, cm^3 cm^{-3}; Ma: macroporosity, cm^3 cm^{-3}; Mi: microporosity, cm^3 cm^{-3}; FC: field capacity, cm^3 cm^{-3}; PWP: permanent wilting point, cm^3 cm^{-3}; AW: available water capacity, mm.

Eigen: eigenvalues; Var.: variance explained by each parameter, %; Cum: cumulative variance explained.

*Values in bold in each PC column were used to select the minimum data set (MDS).

In 2012/2013 season, PC1 had BD, Pt and Ma variables with high loading rates, with both BD and Ma retained based on the reason stated above. PC2 had TN, SOM and Cpool with highest loading rates, however TN and SOM were retained as representative of nutrient storage and organic matter based on loading rate and correlation sum. PC3 had Mi and AW as variables with high loading rates, however AW had highest loading rate and communality and was selected for MDS. So, 2012/2013 season had BD, Ma TN, SOM, and AW as the MDS.

In 2013/2014 season, there were four (4) PCs, however the PWP and C/N in PC4 were dropped for better comparison, thus BD, Ma, TN, OM and AW were the MDS used to evaluate soil quality status of the 0-10 cm layer of the tung field.

For the 10-20 cm layer, BD, Ma, TN, OM, and AW were selected as the MDS based on the same analysis performed for the 0-10 cm layer (Table 33).

6.8.2 Soil quality index (SQI)

The mean values of soil quality index (SQI) of the tung-based cropping system at initial (May 2012) and at the end of 2012/2013 and 2013/2014 growing seasons are shown in Figure 42. There was no significant difference ($p<0.05$) in the average SQI values in both the 0-10 and 10-20 cm soil layers at the beginning of the experiment in year 2012 and at the end of both 2012/2013 and 2013/2014 growing seasons.

Shortly before the imposition of crop rotation and intercropping treatments in year 2012, the 0-10 cm surface layer had average values of SQI between 0.429 and 0.506. At harvest of 2012/2013 season, the average values of SQI ranged from 0.507 to 0.612, slightly increased in TCS/So+I, TCS/So+O and TOtP treatments while it remained at par in control (sole tung) treatment. At harvest of 2013/2014 season, the SQI were between 0.482 and 0.609, slightly reduced in TCS/So+I treatment, increased in TCS/So+O and TOtP treatments and reduced in control treatment (Figure 42).

For the 10-20 cm layer, lower values of SQI were recorded in every evaluation, compared with the surface layer, with average values between 0.444 and 0.496; from 0.306 to 0.353; and 0.285 to 0.381 for the initial, 2012/2013 and 2013/2014 growing seasons, respectively (Figure 42).

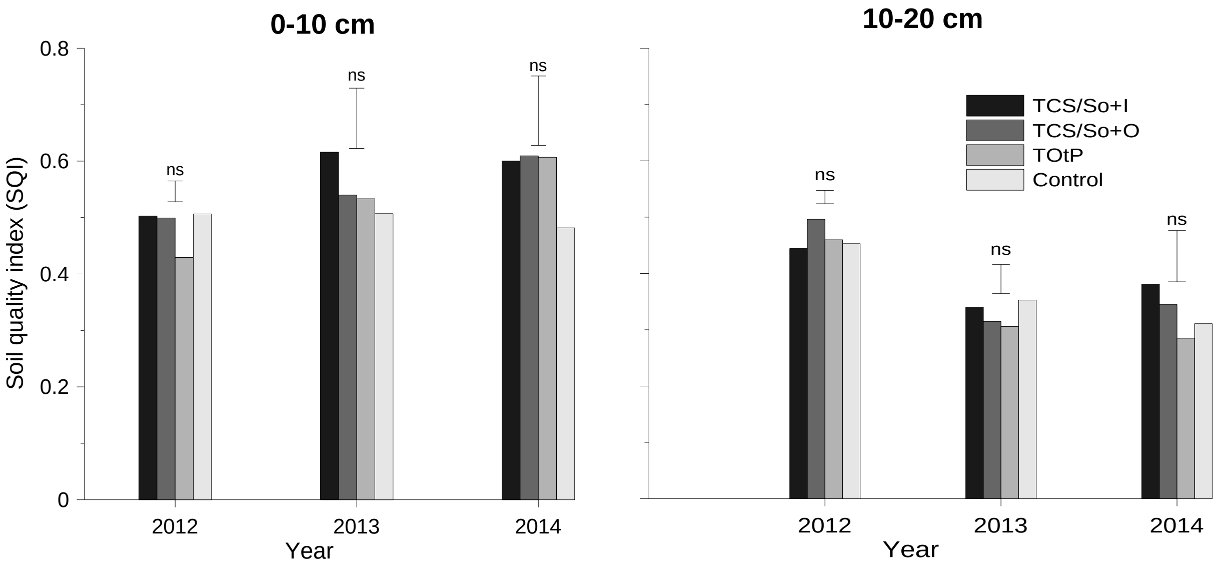


Figure 42. Mean soil quality index (SQI) values of the tung-based cropping system at initial (May 2012) and at the end of 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

TCS/So+I: tung-crambe-sunflower/soybean rotation + inorganic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean rotation + organic fertilizer; TOtP: tung-oats-peanut rotation; Control: sole tung.

*significant; ns: not significant at 5% level of probability by Fisher's LSD test.

The vertical bars represent the least significant difference (LSD).

Irrespective of soil layers, the pooled SQI values did not significantly differ among the different cropping treatments, although the SQI of control treatment appeared to decrease in magnitude on seasonal basis (Figure 43a). Regardless of cropping treatments, the average values of SQI of the tung field did not significantly differ ($p<0.05$) between the 0-10 and 10-20 cm layers at initial (2012), however, there was significant differences ($p<0.05$) in the average values of SQI between the 0-10 and 10-20 cm layers at harvest of both the 2012/2013 and 2013/2014 growing seasons (Figure 43b).

The relative contribution of the limiting factors to the average soil quality index (SQI) of the 0-10 and 10-20 cm soil layers of the tung field is presented in Figure 44. For the 0-10 cm layer, water retention and permeation factor, represented by Ma was the highest contributor (about 31%) to the average SQI values in both growing seasons, followed by BD (20%), soil organic matter (18%) while total nitrogen was lowest contributor (11%). For the 10-20 cm layer, there was no discernible trend regarding the relation contribution of the soil quality indicators. The AWmax was the highest contributor (about 29%) in 2012/2013 growing season while Ma was the highest contributor (about 27%) at the end of 2013/2014 growing season (Figure 44).

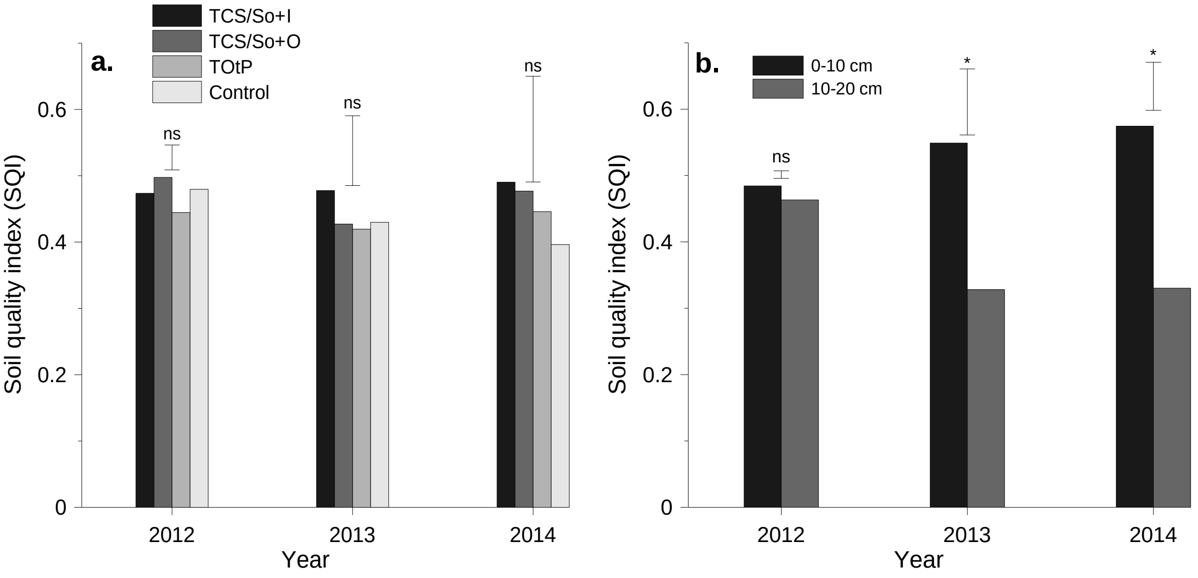


Figure 43. Mean soil quality index (SQI) values of the tung-based cropping system (a) irrespective of soil depth and (b) irrespective of cropping treatments, at initial (May 2012) and at the end of 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

TCS/So+I: tung-crambe-sunflower/soybean rotation + inorganic fertilizer; TCS/So+O: tung-crambe-sunflower/soybean rotation + organic fertilizer; TOtP: tung-oats-peanut rotation; Control: sole tung.

*significant; ns: not significant at 5% level of probability by Fisher's LSD test.

The vertical bars represent the least significant difference (LSD).

6.8.3 Management goals and soil quality indicators

The relationship between selected soil quality indicators and management goals, represented by tung plant height and soil function of profile water retention, is presented in Tables 34 and 35. The analysis of variance (ANOVA) showed that the regression of tung plant height from the selected soil quality indicators of both soil

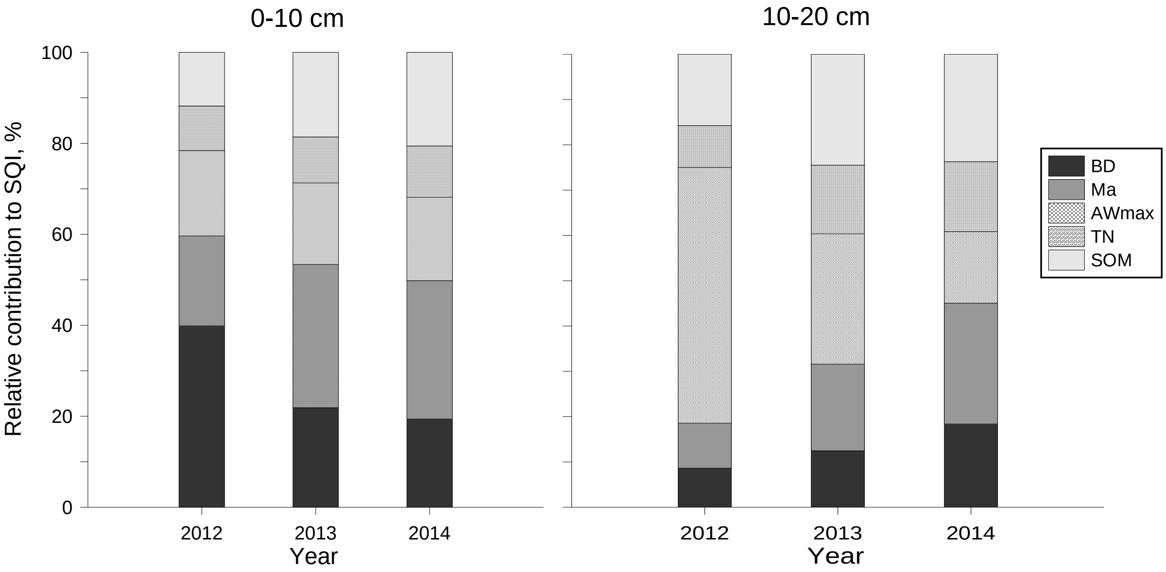


Figure 44. Relative contribution of each limiting factor to mean soil quality index (SQI) values of the different soil layers of the tung-based cropping system at initial (May 2012) and at the end of 2012/2013 and 2013/2014 growing seasons at Santa Maria, Brazil.

BD: bulk density; Ma: macroporosity; AWmax: maximum available water; TN: total nitrogen; SOM: soil organic matter.

layers and the two seasons was not significant ($p<0.05$). For the tung plant height, the regression correlation coefficient, R, was 0.50 at harvest of 2012/2013 growing season while it reduced to 0.33 at the end of 2013/2014 growing season (Table 34). Likewise, the analysis of variance (ANOVA) showed that the overall regression of soil profile water retention and the selected soil quality indicators was not significant ($p<0.05$) during the two consecutive growing seasons. The regression correlation was low, with correlation coefficient, R, ranging from 0.34 to 0.56 (Table 35).

Table 34. Relationship between selected soil quality indicators and management goal of tung plant height during 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

Regression equation		
2012/2013 growing season	R	F-value
$PH = 2.70 + 0.17BD + 2.60Ma + 2.25AWmax + 4.97TN - 3.07OM$	0.50	0.36^{ns}
2013/2014 growing season		
$PH = 3.49 + 0.34BD + 1.04Ma - 4.61AWmax - 1.10TN + 0.83SOM$	0.33	0.82^{ns}

PH: plant height, m; BD: bulk density, g/cm^3; Ma: macroporosity, cm^3 cm^{-3}; AWmax: maximum available water, cm^3 cm^{-3}; TN: total nitrogen, g/kg; OM: organic matter, %.

R^2: coefficient of determination;

*significant and ns: not significant at 5% level of probability by ANOVA.

6.8.4 Tung plant height and soil quality index (SQI)

The quantitative relationship between SQI and management goal of tung plant height was made, using plant height as dependent variable and SQI as independent variable. The linear regression equations, correlation coefficient, R, and p-value are given in Table 36. The R values are generally low, 0.008 to 0.04 for the 2012/2013 and 2013/2014 growing seasons, respectively, while the p values showed that the relationship was non-significant, however, the coefficients of SQI in the regression equations were positive.

Table 35. Relationship between selected soil quality indicators and soil functional goal of profile water retention of the tung field during 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

	Regression equation		
Location	2012/2013 growing season	R	F-value
Close to tung	$WR = 221.7 - 1.6BD + 7.4Ma + 27.6AWmax + 27.4TN - 17.6SOM$	0.34	0.48^{ns}
Within intercrop	$WR = 206.2 + 3.1BD + 5.4Ma + 14.6AWmax - 36.7TN + 21.4SOM$	0.40	0.67^{ns}
	2013/2014 growing season		
Close to tung	$WR = 329.8 - 48.3BD + 119.2Ma - 152.1AWmax - 32.5TN + 17.1SOM$	0.35	0.51^{ns}
Within intercrop	$WR = 150.7 + 24.8BD + 94.5Ma + 147.5AWmax - 20.1TN + 10.1SOM$	0.56	1.61^{ns}

WR: profile water retention, mm; BD: bulk density, g/cm^3; Ma: macroporosity, cm^3 cm^{-3}; AWmax: maximum available water, cm^3 cm^{-3} ; TN: total nitrogen, g/kg; SOM: soil organic matter, %.
R^2: coefficient of determination;
*significant and ns: not significant at 5% level of probability by ANOVA.

Table 36. Relationship between management goal of tung plant height and soil quality index (SQI) during 2012/2013 and 2013/2014 growing seasons at Santa Maria, southern Brazil.

Growing season	Regression equation	R	P-value
2012/2013	$PH = 2.68 + 0.022SQI$	0.008	>0.967
2013/2014	$PH = 3.88 + 0.12SQI$	0.040	>0.864

PH: tung plant height, m; SQI: soil quality index.
R: correlation coefficient; P-value: level of probability.

7 DISCUSSION

7.1 Effect of cropping effect on soil properties of the tung field.

7.1.1 Soil bulk density and porosity

The initial average BD values of the 10-20 cm layer were slightly higher than those of the surface layer, this may be attributed to effect of previous site management (BD history) before transplanting of tung.

There was no discernible trend in the average values of BD of the 0-10 cm surface layer for the TCS/So+I, TCS/So+O and TOtP treatments while that of control (sole tung) increased slightly at harvest of 2013/2014 growing season compare with the initial value (Table 27). This result was similar to previous findings of NISSEN et al. (2001) and FAN et al. (2006). Although the average values of BD of the 10-20 cm subsurface layers increased with season, however, the significantly highest value of 1.68 g/cm^3 obtained from the TOtP treatment was below 1.75 g/cm^3 considered as threshold value to limit root growth (COLLARES et al., 2006, REICHERT et al., 2009a). Therefore, the soil has not offered impediment to water flow, gaseous exchange and root growth. In addition, the peanut extensive root system and pod formation may be responsible for the significantly highest average BD values obtained in the 10-20 cm layer of TOtP treatment as a result of biophysical activities as the roots and pods tend to enmesh and compress groups of soil aggregates into larger aggregates. Moreover, water uptake by plant roots promotes differential dehydration, with an increase in BD near the root zone as a result of soil adhesion (YOUNG, 1998). In the control treatment, the continuous increase in BD especially in the surface layer may be as a result of raindrop impact and alternate soil wetting and drying cycles (LEIJ et al., 2002). It is worthy to note that this BD has not pose limitation to tung root growth, however if the BD increase in this manner, it can prejudice water infiltration and increase surface runoff, which may cause substantial soil and nutrient loss.

The soil total porosity of the 0-10 cm layer slightly improved in the intercropping and crop sequence systems (TCS/So+I, TCS/So+O and TOtP treatments) while that of sole tung remained unchanged at harvest of 2012/2013 growing season compared with the initial values. At the end of 2013/2014 growing season, the Pt remained unchanged in the TCS/So+I, TCS/So+O and TOtP treatments and reduced slightly in the control treatment compare with the values of previous season (Table 28). With intercropping and rotation of oats, sunflower, crambe and soybean in the tung-based agroforestry, there are more litter and roots in the soil top layer, thus the litter and root biomass per unit area increased, which resulted in increased aggregation and improve the pore space increment. In pure or sole tung, the alternate drying and wetting cycles cause continuous movement and rearrangement of soil particles, as a result, soil structure becomes stronger and the total soil pore space becomes reduced (LEIJ et al., 2002). For the subsoil layers, the Pt of all the treatments were lower than that of the surface layer and there was a slight reduction at the harvest of both 2012/2013 and 2013/2014 growing seasons compared with initial values. The reason for lower Pt in the subsurface layers may be due to lower soil organic matter content and reduced biological activity that could have contributed to soil aggregation and improve the pore space.

The initial average values of Ma in the 0-10 cm layer of the young tung field were approximately or more than 0.10 cm^3 cm^{-3} considered as minimum for adequate water movement and gaseous exchange (DREWRY, 2008). Silveira Neto et al. (2006) found that crop sequence system with that other cultivars enhanced macroporosity. In the sub surface layers, the values were less than the threshold, especially in the 20-40 cm layer, indicating poor soil condition. Intercropping and crop sequence treatments improved the Ma in the 0-10 cm layer after each growing season (Table 28). This may be attributed to the creation of biopores by intercrop root systems, more aggregation and increased pore space by the increase in SOM, thus providing better soil environment for many microbes and plant roots, which requires aeration as well as enhance water movement. The reduced Ma in sole tung treatment may be as a result of reduction of pore space by alternate drying and wetting cycles and absence of biopores. In the sub surface layers, the Ma values remained below 0.10 cm^3 cm^{-3}, showing that the overall effect of intercropping and crop sequence is limited to the surface layer, thus a need for other measures that would reverse the trend. These findings are in agreement with the results of Fan et al. (2006) in their study on the effects of intercropping systems of trees with soybean on soil physico-chemical properties in juvenile plantations.

7.2.2 Field capacity, permanent wilting point and maximum available water

As mentioned earlier, the amount of water retained at suction levels below -100 kPa, such as at field capacity (FC, -10 kPa), depends primarily on capillary effects and pore-size distribution, and is therefore strongly influenced by soil structure. In this study, there was no discernible trend in the soil volumetric water contents at field capacity (FC) among the different cropping systems as it either increased or decreased after each season with respect to the initial values (Figure 37). However, soil water content values at FC decreased in the 10-20 cm layer while it increased in the 20-40 cm layer. This may be attributed to natural variability due to soil structure. Soil texture also has effect on water retention at FC. For the superficial layer that is of sandy texture, most of the pores are relatively large, and once these are emptied, only a small amount of water remains. In the 20-40 cm deeper layer with higher clay content, the higher value of soil water content at FC may be as a result of more uniform pore-size distribution. The reduction in water content at FC obtained in the 10-20 cm layer requires further study.

The soil volumetric water contents at permanent wilting point (PWP, -1500 kPa) did not vary much in the 0-10 cm surface after each season in relation to initial values, however there was increase in the average values of soil water content at PWP of the 10-20 and 20-40 cm layers in each season compared with the initial values (Figure 37). Likewise, there was no discernible trend among the different treatments although, the soil volumetric water contents at PWP was slightly higher with soil depth. The increase in PWP with soil depth is due to the difference in specific surface and adsorption between the sandy and clayey textures. In this site, the surface layer had more sand content while the deeper layers had more clay content, this explains the difference in the amount of water retained at PWP with depth, as clay exhibits higher specific surface and adsorption of water films to the particle surface. Water retention at this potential (-1500 kPa) is a function of soil texture and mineral composition rather than soil structure.

The combination of water content at FC and PWP resulted into maximum water available (AWmax) for root extraction and is a function of soil texture and mineral composition. For the 0-10, 10-20 and 20-40 cm layers considered for this study, there was no discernible trend in the values of FC and PWP among the treatments in each season (Table 29), thus there was no trend in soil AWmax among the different treatments. The total soil profile AWmax at the end of second season was reduced compared with the initial values in 2012, this can be attributed to complex interaction of soil physico-hydraulic properties on water retention (ARAUJO et al., 2004). The correlation analysis showed that the AWmax was positively and significantly correlated with the Pt and FC whereas the correlation was significant negative correlation with the BD and PWP Appendix II).

7.3.3. Soil saturated hydraulic conductivity

According to Timm & Reichardt (2004), saturated hydraulic conductivity depends on water fluidity, which is proportional to its viscosity and soil bulk density as well as macroporosity which is a function of soil texture and structure and also varies with time (BORMANN and KLAASSEN, 2008; HU et al., 2009). The high initial saturated hydraulic conductivity (Ksat) in the 0-10 cm surface layer of this soil is attributed to soil mobilization by ploughing and harrowing prior to transplanting of tung (Figure 38). This recently tilled layer is characterized by low bulk density and larger pore volume. The low initial Ksat values in the subsurface layers were due to low macropore volume and high BD obtained in these layers, which are antecedent soil conditions.

The increase in Ksat values of the surface layer at harvest of both 2012/2013 and 2013/2014 growing seasons is as a result of increased root activities by intercrops. The creation of biopores by intercrop root systems and increased pore space due to increased SOM enhance water movement. The Ksat is a dynamic soil property and its behaviour is determined by the degree of compaction of the soil (REICHERT et al., 2007) and highly dependent on the shape, arrangement, quantity and continuity of pores in the soil, having a direct relationship with the transport capacity of solute and chemicals (MESQUITA and MORAES, 2004). In contrast, the decrease in Ksat value in the surface layer of sole tung treatment is attributed to reduced macropore volume and increased BD as a result of soil reconsolidation due to raindrop impact. This relationship is confirmed as the Ksat showed significant positive correlation with the Pt and significant negative correlation with the BD (Appendix II). Fine soil particles tend to be easily scattered by rain drop splash of aggregate instability due to the sandy texture, and the particles are transported by infiltrating water, clogging some soil macropores in the process. Similar changes have been reported by Moret and Arrúe (2007).

There was no discernible trend in Ksat of the subsurface layers over the seasons. This may be due to the fact that it is only the surface layer that was subjected to manipulation by the cropping treatments. Also the use of diverse intercrops with different rooting systems may influence the pore geometry differently, thus the indiscernible trend in Ksat.

7.3.4 Organic matter, Cpool, C/N ratio and total nitrogen

The SOM content of the 0-10 cm superficial layer of intercropping system and crop sequence systems as well as the sole tung decreased after the first season with respect to the initial SOM. The reduction in SOM content in the end of the first growing may be attributed to loss of carbon in the form of carbon dioxide (CO_2) from this soil (Table 30). The sandy nature of the soil is an indication of being a well-drained and thus there is quick oxidation of organic carbon, especially in the surface layer. In treatments with intercrops, the relatively short period of one year may not have pave way for appreciable increase in organic matter content because when soil organisms digest organic matter newly applied residues, part of the carbon originally in these residues is used for growth and cell division by microorganism, with the rest being emitted as carbon dioxide, then the concentration increases as decomposition progresses, with the amount or speed varying with the C/N ratio of the residue (REHM, 2010). Therefore, higher SOM values were obtained from TCS/So+O and TOtP treatments at the end of fourth intercropping and crop sequence in 2014. The TCS/So+O treatment received additional organic manure while TOtP treatment had higher amount of residues from oats and peanut at planting of intercrop in each season. In addition, root exudation, death and decay provide source of food for microorganisms, promoting microbial activity (SIX et al., 2004). Thus changes of the kinds and quantities of microbes taking part in the degradation of organic matter can indirectly influence SOM content of the soil (CHENG, 1994). In a study by Fan et al. (2006), the soil organic matter content was higher in larch/soybean and ash/soybean intercropping than in pure larch and ash treatments, respectively. Likewise, Guimares et al. (2014) working on soil aggregation and organic carbon of Oxisols under coffee in agroforestry systems found higher soil organic carbon in intercropping systems compared with conventional coffee.

The effect of repeated application of inorganic N in TCS/So+I treatment at planting in each season caused rapid loss of humus (Anon., 2014), thus the reduced SOM content. The SOM content in sole tung was less than 1% after the second growing season, which may be attributed to carbon loss and limited replenishment by few tung leaves that normally drop in June as a result of low temperature, thus it may not be possible to achieve tung potential growth and fruit yield. According to Kay and Angers (1999), crop potential yields become impossible if the SOC contents are below 1%, irrespective of soil type.

For the 10-20 cm sub surface layer, the decrease in SOM content is attributed to lesser amount of plant biomass inputs which could have contributed to SOM build up.

The average values of Cpool of the surface layer of all the treatments also decreased with season. This is expected because the both the BD and SOM content of the intercropping and crop sequence systems decreased after the first season, whereas, the reduction in sole tung generally resulted from greater reduction in SOM content as its average BD increased. Even in TCS/So+O and TOtP treatments where the SOM content increased after the second year, the reduced Cpool may be attributed to decrease in BD as Cpool is directly proportional to both BD and organic carbon. The highest average value obtained in TCS/So+O treatment may be due to higher organic matter build up from additional organic manure application (Table 30). The lower Cpool in the sub surface layer is a follow up of reduced SOM content in this layer. Abid and Lal (2008) also reported lower Cpool with increasing soil depth.

Nitrogen plays a vital role in plant and soil functions. The treatments that received additional organic manure and higher amount of residues had higher TN in the 0-10 cm surface layer after each growing season (Table 30). Moreover, soybeans fix atmospheric nitrogen and this increases the mineral soil nitrogen content as well as benefits other neighbouring plants (WANI et al., 1995), such as the tung plant in this study. The more readily available N can result in increased plant biomass, with the consequence that more litter becomes available for decomposition processes (BLACK et al., 2010). Adequate TN will not only affect above-ground biomass but also influence below ground biomass by increasing root biomass and volume of soil proliferated. This in turn has positive effect on soil organic matter mineralization and other rhizophere activities.

In this same surface layer, the TN contents in TCS/So+O and TOtP treatments were higher compared with TCS/So+I treatment that received inorganic N at planting. This may be due to the creation of nitrogen via mineralization of the readily decomposable organic manure and crop residues that exceeds its removal by immobilization process. The average TN content in TCS/So+I did not vary with time, this may be due to the fact that mineralization process equates immobilization of inorganic nitrogen applied.

There was no consistence in the results of TN in the 10-20 cm subsurface layer, however the values are consistence with the SOM content distribution. According to Wang et al. (1994), available nutrients come from the decomposable material of the soil organic matter.

The decomposition and subsequent turnover of carbon and nitrogen in soil is influenced by the C/N ratio of both soil and litter (Black et al., 2010). The C/N ratio of both the surface and subsurface layers of the tung field were within the 10:1 and 15:1. However, the C/N ratio decreased after each season (Table 30). According to Black et al. (2010), less than one-third of the applied carbon in fresh residue remains in the soil after the first few months of decomposition, as the material is decomposed, the C/N ratio decreases.

The non-significant effect of cropping systems on these variables is attribute to the fact that the time required for responses to become significant may be several years as it is a function of the organic matter in the soil, inherent nutrient limitations, climate among other factors (BLACK et al., 2010).

7.3.5 Degree of compaction

As already mentioned, the DC is an important parameter used to identify soil compaction affecting crops as a result of management practices (REICHERT et al. (2009a). The DC values of the 0-10 cm surface layer of all the treatments were within the range of the optimum DC of 77-88% for crops proposed by Suzuki et al. (2007) and below the maximum DC of 90% proposed by Reinert et al. (2008). Similarly, the DC values of the 10-20 and 20-40 cm sub surface layers were also within the 77-88% optimum range, except in T3 treatment with peanut as intercrop. The reduction in DC values from TCS/So+I, TCS/So+O and TOtP treatments compared with initial values (Table 31) is a direct indication of decreased bulk density, indicating the positive effect of intercrop in these treatments, thus improved soil physical conditions for both tung and intercrops. Although Suzuki et al. (2007) stressed that crop yield may be reduced if the degree of compaction is too low, as the soil become loose, which could affect soil-root contact and decrease rhizosphere activity. On the other hand, the increasing DC from control (sole tung) treatment showed that the soil may soon reach the critical bulk density, and thus under the state of high compaction which is undesirable in view of soil quality and functions.

7.4 Soil water retention

Soil water retention (SWR) under agroforestry systems fluctuates with alternate soil drying and wetting cycles, caused by rainfall distribution that occur during the growing season, extraction and competition for water by tree plants and intercrops, and other hydrologic processes.

The average soil profile water storage close to the tung plant was lower than within the intercrop at the beginning of the experiment in June of 2012/2013 and 2013/2014 growing seasons. This is attributed to water extraction by the tung plants, an indication that the tung trees continued to deplete available soil water. Similar observation was reported by Chirwa et al. (2007) in a study on soil water dynamics in systems containing *Gliricidia Sepium*, pigeon pea and maize in a sandy loam soil in southern Malawi. The SWR measured near the tung plant on 04/07/2012 and 14/07/2013 increased. Likewise, the SWR tended to increase or even decreased within the intercrop rows (Figures 39 and 40). The large increase observed near the tung plant in 2012/2013 is attributed to the combined effects of cumulative recharge from rainfall and increased infiltration due to high macropores arising from soil mobilization, while the relative increase in 2013/2014 growing season is due to higher cumulative recharge from rainfall. The relatively small decrease in profile SWR observed within the intercrop rows may be due to water use by the intercrops which may have reduced available water.

With increased evaporative demand in August and September as well as the vegetative growth stage of the intercrops, there was more water extraction by the intercrops for transpiration, thus the profile SWR decreased significantly within the intercrop rows. Although the tung plants are just developing new leaves during this period, the rate of transpiration will be low, and that of evaporation from the uncovered soil surface is increased compared with the surface environment of the winter oats and crambe (intercrops), thus the reduction in profile SWR near the tung stands. The reduction observed in TCS/So+I, TCS/So+O and TOtP treatment is attributed to water extraction by roots of intercrops. The addition of arable crops to conventional tree components may increase water use by using water which the other component could not be used, signifying complimentary water use. According to Chirwa et al. (2007), this is essentially true for agroforestry systems, as they offer substantial scope for spatial and temporal complementarity of water use resulting from improved exploitation of soil water reserve. Another school of thought is that the presence of intercrops modifies the soil micro-climate as water extraction by intercrops creates low water potential within the rhizosphere, thus water moves in the direction higher water potential to that of lower potential to maintain equilibrium. In sole tung (control treatment), the profile SWR near the plant and outside was higher and uniform, as there was no external influence on soil water reserve. At harvest of both growing seasons, the profile SWR was at par the because the soil surface condition is virtually the same, the few and small leaves on the tung plants were not enough to create enough shade at to protect the surface from evaporation. Although the profile SWR increased, this was a result of cumulative recharge from rainfall.

During the summer period of both growing seasons, profile SWR decreased with time, following the course of prevailing climatic condition (Figures 39 and 40). Between the months of November and February of both growing seasons, the atmospheric demand (ETp) was higher than recharge by rainfall, thus soil water content continued to decrease. During this period, the intercrops showed stress effect because of water deficit during the initial and vegetative growth stages. On the other hand, the tung plants was not affected by the water deficit. The stress observed in the intercrops was as a result of concentration of roots in the surface layer that is more prone to evaporation. Also the compacted 10-20 cm layer offer impedance to root penetration to extract water from deeper layers. This is evidence that shallow-rooted crops suffer the negative effects of compacted soil layers during periods of prolonged droughts (KAISER, 2010). To forestall physiological wilting, a 12-mm irrigation depth was applied in November of 2012. In contrast, the young tung plants possess different rooting patterns, the tap roots may have penetrated the compacted layer during period of adequate water availability and thus able to extract water from deeper layers. During the water deficit of summer period, the significant lowest profile SWR obtained outside sole tung was as a result of bare soil while the highest value in TOtP treatment was due to complete ground cover by peanut (Figure 26 b). In systems where the crop does not provide complete ground cover during the growing season, especially during this critical period, results in high evaporation from the soil surface accounting for 30-60% of annual rainfall (WALLACE, 1996). Very close to the tung plant, the soil dynamics was similar and not significant during the first season while significant difference was observed during the second season (Figures 39and 40).

The profile SWR increased as the climatic conditions changed, with more rainfall events from late February of 2012 and January of 2013 until harvest. At harvest, the non-significant difference in profile SWR retention close to tung plant may be due to relatively uniform soil conditions in this region while within the intercrop and away from tung plant in sole tung plot, the effect of ground cover was still dominant.

In general, the seasonal variability of profile SWR of the different treatments followed the course of climatic conditions as well as the effect of intercropping and crop sequence systems. Reichert et al. (2011) affirmed that water availability to plants depends not only on the capacity of the soil to retain water and make available to plants, but also on the behaviour of hydrologic cycle during the growing season as well as management practices.

7.5 Tung plant height

As expected, tung plant height increased and the increment varied as a function of crop management. The tung plant in TCS/So+I, TCS/So+O and TOtP treatments under cropping and soil amendment practices showed higher growth compared with sole tung (control) (Figure 41). This is attributed to organic matter build up and more important, nitrogen availability. The highest plant height obtained from TCS/So+I treatment may be due to the application of inorganic N fertilizer which was also manifested in the deeper layer of this treatment. It is established that the vegetative growth of a plant is primarily controlled by N availability (SHARMA et al., 2005). The absence of crop sequence-based cropping system of the sole tung led to the onset of changes in soil chemical, physical and biological factors, which could compromise the stability of crop growth (FRANCHINI et al., 2011).

7.6 Soil quality index

Soil quality index (SQI) is the integration of one or several measures of soil physical, chemical and biological indicators. The non-significant effect of cropping systems on the overall SQI in both soil layers and irrespective of soil layer (Figures 42 and 43a) is in line with the results on the effect of cropping systems on the soil quality indicators that were integrated into a single SQI, indicating relatively too short to obtain any significant effect of the cropping system. Similarly, the significantly higher SQI in the 0-10 cm superficial layer at harvest of both growing seasons agrees with the differences in the values of the soil quality indicators between the two layers (Figure 43b). Therefore, the intercropping and crop sequence systems that increased litter and roots biomass accumulation and subsequent decay and decomposition (FAN et al., 2006) as well as additional application of organic manure to this layer contributed to these processes. For the 10-20 cm layer, the general reduction of SQI is attributed to increased BD and lower values of Ma, AWmax, OM and TN. This is expected because the effect of the crop residues and soil amendment on soil properties and processes occur mainly in the surface layer. Aziz et al. (2011) working on crop rotation impact on soil quality also reported decreased SQI with increasing soil depth.

The performance of the treatments in terms of SQI showed that TCS/So+I, TCS/So+O and TOtP treatments are sustaining and aggrading while that of sole tung is degrading (Figure

43a), therefore strategies aimed at ensuring soil and water conservation are highly needed for the sole tung plots.

As already observed in sugarcane experiment, the highest contribution from water retention and permeation showed that its good conditions are prerequisites for optimum biological activity and nutrients transformation and cycling. Similarly, organic matter and nutrient concentrations, such as TN, in the soil are more important for soil to resist structural degradation and fertility, respectively (AJAMI et al.; SHUKLA et al., 2006).

The positive correlation between the selected SQ indicators and management goals of tung growth (plant height) and soil water retention clearly showed that the selected minimum data set, BD, Ma, AWmax, TN and SOM are key indicators of soil quality which highly influenced the soil functions and overall soil quality of the young tung-based agroforestry system. Likewise the correlation between tung plant height and SQI was positive. However, the low correlation and non-significance of the regression analysis is an indication that those two years are not enough for the treatments to show any significant expression as well as complex interaction arising from the use of different crop species for the intercrops. This agrees with the findings of Erkossa et al. (2007) who attributed it to interaction of other several variables such as climate and crop species.

8 CONCLUSIONS

The seasonal pattern of soil quality status, soil water and thermal regimes and performance of sugarcane (three consecutive seasons) and tung tree plant (two consecutive seasons) under different management practices was investigated.

Except the Ma of the 0-10 cm surface layer, soil tillage did not significantly affect soil physical properties. The BD and Ma slightly decreased and increased, respectively in the 0-10 cm surface layer of all the tillage treatments over the season. The 10-20 and 20-40 cm sub surface layers of sugarcane field showed some degree of compaction, although it did not affect sugarcane growth. The NT treatment did not store more water than other tillage treatments in all the soil layers.

Residue mulching did not significantly affect the various soil properties evaluated. There was no consistency among the initially tilled and untilled plots as well as residue mulching as regards soil mechanical properties of pre-compression stress and compression index. There was no discernible trend and significant difference in sugarcane ratoon yield among the tilled and no tilled plots. Similarly, sugarcane yield did not differ between the residue mulch treatments. Both tillage and residue mulch treatments did not significantly influence SQI. The different tillage treatments exhibited varying degree of superiority with respect to SQI, the order was NT>NTC>CT>Chi; NT>CT=Chi>NTC and NT=Chi>NTC=CT at harvest of 2010/2011, 2011/2012 and 2012/2013 growing seasons, respectively. Residue mulch treatment had no significant effect on SQI. In general, the soil quality index (SQI) values of the subsurface layers were generally low, indicating the soil is degraded due to low fertility status.

There was significant temporal variation of soil water status among the soil depths. The mean values of soil matric potential significantly differed due to residue mulching in both growing seasons and were higher in no mulch plots in both seasons. All the variables except precipitation were autocorrelated. Soil water storage also correlated with other soil-atmospheric variables, however, the values were not the same for the soil depths and the treatments.

Higher average, maximum, minimum and amplitude of soil surface temperature were observed in no tilled (NTC and NT) treatments. Residue mulching significantly modified the soil thermal regime, as the maximum soil temperature of the surface layer was suppressed as much as 11 ^{o}C and reduced the average daily temperature by about 4 ^{o}C during the critical summer period. Therefore, residue mulching could mitigate deleterious effects of supra-optimal temperature, such as excessive evaporation, soil heating, etc. During the critical winter period, the surface layer average and maximum temperature increased by about 3 and 4 ^{o}C, respectively, indicating residue mulching could protect the soil from extreme cold thermal conditions that could make soil nutrients immobile and soil micro-organisms dormant.

Residue mulching significant affected the covariance structure of the average daily soil temperature by the differences obtained in the magnitude of the temporal range and sill variance.

The estimation of both soil water storage and temperature using state-time analysis performed better than the corresponding classical statistical linear regression, because of higher coefficient of determination as well as being able to incorporate measurement and model errors.

The effect of missing data on the reliability of the state-time analysis was consistently taken care of as the more the proportion of missing data increases, the performance parameters of the estimation process decreases.

Except for the Ksat of the 0-10 cm surface layer, cropping systems did not significantly affect the hydro-physical properties of the tung soil. Also, the degree of compaction was within the optimum range, however the sole tung plot could reach the critical state with time.

For the tung experiment, the significant higher reduction in profile SWR observed in within intercrops of TCS/So+I, TCS/So+O and TOtP treatments during the winter period due to water use by the intercrops which may have reduced available water, whereas in sole tung (control treatment), the profile SWR outside was higher and uniform, as there was no external influence on soil water reserve. During the summer period of both growing seasons, the decrease in profile SWR within the intercrops was a combined effect of high evaporative demand of the atmosphere and root water uptake while very close to the tung plant, inconsistence results were observed. The tung plant in TCS/So+I, TCS/So+O and TOtP treatments under cropping and soil amendment practices showed higher PH with time compared with sole tung, although no significant difference in PH for any given season.

Cropping system did not significantly influence SQI while the general performance of the treatments showed that TCS/So+I, TCS/So+O and TOtP treatments are sustaining and aggrading while that of sole tung is degrading

9 RECOMMENDATIONS

Based on the results and conclusions of this study, the following recommendations were drawn for consideration:

1. The low and decreasing soil quality index (SQI) values of the soil layers of the sugarcane field calls for urgent measures such as removal of the sugarcane and allow to fallow.

2. To ensure consistence result (if would be) from tillage treatment in studies involving seasonal monitoring of soil physical, hydraulic and mechanical properties, application of tillage at the onset of each season is recommended.

3. A detailed water balance and consumptive water use of sugarcane is still lacking in this region, hence the use of lysimeter and other weather related equipment should be considered for future studies.

4. The non-significant results of soil quality indicators obtained from tung experiment resulted from the short-term evaluations, thus requiring long-term studies to achieve any significant effect from the use of intercropping and crop sequence in the tung-based agroforestry system.

5. Similarly, there is dearth of information on consumptive wateruse and related parameters required for water balance studies in this system, thus future studies should focus in this area.

6. Under field conditions, the state-time analysis has been able to evaluate the temporal relationships between soil water storage and temperature and other soil-atmospheric variables and could be a useful tool for modeling, farm management, and of potential importance to farmers since it could ensure the possibility of making good predictions of these variables. Future studies should incorporate other dynamic soil variables related to these properties and validation using data observed in another region or season.

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APPENDICES

Appendix I. Correlation between the various soil quality indicators of the sugarcane experiment.

	BD	Pt	Ma	Mi	FC	PWP	AW	TN	OM	CN	Cpool	σ_c	*Ic*
BD	1												
Pt	-.930**	1											
Ma	-.931**	.956**	1										
Mi	-.130	.286	-.008	1									
FC	.089	.050	-.238	.949**	1								
PWP	.391*	-.341*	-.313	-.137	-.039	1							
AW	-.138	.225	-.026	.854**	.842**	-.572**	1						
TN	-.778**	.799**	.703**	.429**	.227	-.369*	.386*	1					
OM	-.766**	.779**	.677**	.444**	.266	-.291	.376*	.979**	1				
CN	.677**	-.674**	-.636**	-.220	-.014	.522**	-.294	-.875**	-.789**	1			
Cpool	.257	-.239	-.286	.120	.267	.190	.116	-.211	-.080	.435**	1		
σ_c	.475**	-.374*	-.407*	.055	.120	.030	.082	-.302	-.316	.199	.233	1	
Ic	-.868**	.803**	.828**	.033	-.133	-.381*	.097	.693**	.688**	-.656**	-.184	-.330*	1

**. Correlation is significant at the 0.01 level (2-tailed).

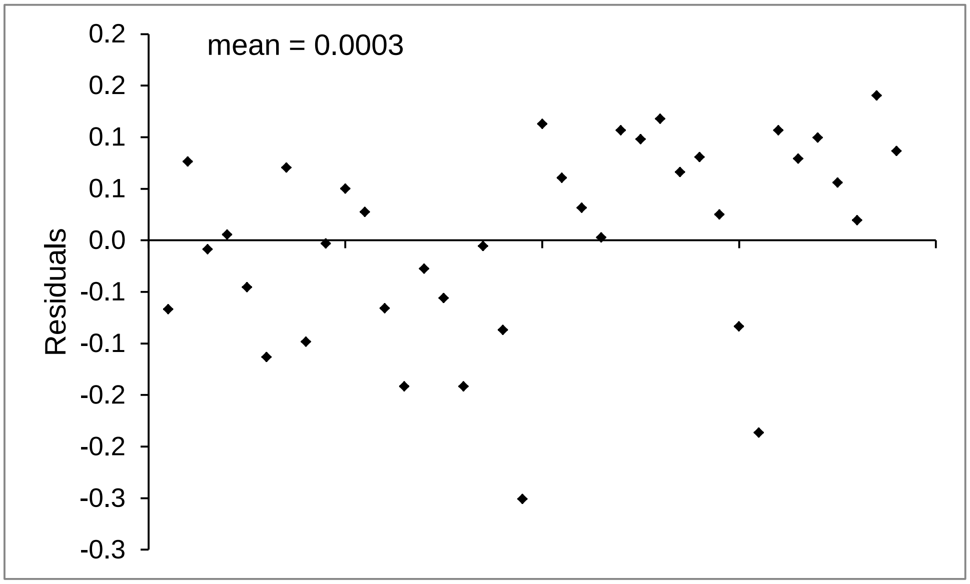
*. Correlation is significant at the 0.05 level (2-tailed).

Appendix II. Correlation between the various soil quality indicators of the tung-based cropping experiment.

	Ksat	BD	Pt	Ma	Mi	FC	PWP	AW	TN	SOM	CN	Cpool
Ksat	1											
BD	-.409*	1										
Pt	.351*	-.946**	1									
Ma	-.123	-.262	.185	1								
Mi	.230	-.255	.357*	-.852**	1							
FC	.216	.109	.004	-.150	.145	1						
PWP	.065	.506**	-.446*	-.418*	.160	.491**	1					
AW	.159	-.372*	.430*	.246	-.004	.554**	-.453**	1				
TN	.483**	-.614**	.654**	-.002	.350*	.388*	.108	.293	1			
SOM	.472**	-.613**	.654**	-.007	.355*	.343	.119	.238	.992**	1		
CN	-.336	.348	-.354*	-.057	-.134	-.487**	.004	-.502**	-.600**	-.498**	1	
Cpool	.498**	-.597**	.622**	-.049	.378*	.336	.164	.187	.942**	.953**	-.454**	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).



Appendix III. Random distribution of residuals (error) of the state-time analysis of the 0-5 cm layer of the sugarcane field.