EFFECTS OF SUGAR CANE PRODUCTION PRACTICES ON SOIL QUALITY IN MAURITIUS

by

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TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 CHARACTERIZATION OF THE STUDY AREA

CHAPTER 4 MATERIAL AND METHODS

CHAPTER 5 INFLUENCE OF SUGAR CANE PRODUCTION ON SOME SOIL BIOLOGICAL PARAMETERS

CHAPTER 6 INFLUENCE OF SUGAR CANE PRODUCTION ON SOME SOIL CHEMICAL PROPERTIES

CHAPTER 7 INFLUENCE OF SUGAR CANE PRODUCTION ON SOME SOIL PHYSICAL PARAMETERS

CHAPTER 8 SUMMARY AND RECOMMENDATIONS

DECLARATION

I declare that the thesis hereby submitted by me for the Philosophiae Doctor degree at the University of the Free State is my own independent work and has not previously been submitted by me at another University. I furthermore cede copyright of the thesis in favour of the University of the Free State.

Signature May 14, 2007

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LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Sugar cane is the most important crop on the Indian Ocean island of Mauritius, covering some 85% of its cultivated area. In spite of the progress in agronomic practices and development of better sugar cane varieties, no apparent gain has been observed in sugar cane productivity over the last twenty years. This situation has raised the question as to whether the soils of Mauritius were not subject to a decline in quality, a phenomenon observed elsewhere on account of sugar cane monocropping. In this context, a study was done to establish whether or not sugar cane production, and the adoption of mechanized practices, were impacting negatively on soil quality, with special attention being devoted to any temporal effect.

This study was conducted between 2002 and 2006 on five sugar estates representing the five major soil groups of Mauritius, namely the P, L, H, B and F groups. To assess the effects of sugar cane cropping on soil quality, pristine soils were compared with sugar cane soils not subjected to derocking and/or land grading. The latter were then compared to sugar cane soils where such land preparation practices had been implemented to assess the effects of adopting mechanized practices. For temporal effects, older cane soils (> 50 years) were compared to younger cane soils (< 25 years) in the P and L groups, and early mechanized soils (> 10 years) were compared to recently mechanized soils (< 3 years) in the P group only. The soil quality parameters that were determined were biological - organic matter and microbial biomass; chemical - pH, cation exchange capacity and exchangeable bases; and physical - particle size distribution, aggregate size distribution and stability to water, bulk density, plant available water, and stabilized water infiltration rate.

Sugar cane cropping had both positive and negative effects on soil quality. These effects were associated with cultural practices, mainly tillage, organic amendments, fertilization, and trash management. Some of these differed according to climate, and therefore led to contrasting results. Topsoil organic matter generally decreased with cropping, probably because of exposure to accelerated decomposition following tillage. Subsoil organic matter increased since tillage also produced mixing of topsoil with subsoil. Topsoil microbial biomass decreased with sugar cane cropping for less material was available for decomposition. The higher subsoil organic matter content had a positive effect on aggregate stability. Addition of organic amendments to the soil generally improved pH, exchangeable bases and base saturation. Acidification also occurred in one instance, probably because of nitrogenous fertilizers. Fertilization increased yields and this led to a higher return of organic matter to the soil. Trash management at harvest played an important role in soil quality. Pre-harvest trash burning lowered the return of carbonaceous material to the soil, whereas trash conservation under green cane harvesting had an enhancing effect.

The adoption of mechanized practices did not affect soil chemical quality. Soil organic matter content decreased following mechanization in the dry zones as a result of increased soil disturbance. The most important effects of the adoption of mechanized practices were on soil physical quality with compaction occurring in the topsoil as a result of mechanized harvesting. Water infiltration rate declined because of reduced topsoil macro-porosity, while plant available water increased.

Soil quality was not systematically aggraded or degraded under long-term cropping in the sub-humid soils of Mauritius, and changes were mainly small and variable. However, soil quality declined with time after the adoption of mechanized practices as large amounts of amendments were initially added to the soil and subsequently allowed to be depleted. The impact of adopting mechanized practices on soil physical quality was observed right from the onset and did not evolve with time.

Soil quality can be enhanced by rebuilding topsoil organic matter levels through trash retention, addition of large amounts of organic wastes and green manuring. The best strategy to combat compaction is prevention, via the use of low-pressure tyres, combined field operations and controlled traffic paths.

Key words: compaction, mechanized practices, organic matter, trash management

UITTREKSEL

Suikerriet is die belangrikste gewas op die Indiese Oseaan eiland Mauritius en dit beslaan ongeveer 85% van die bewerkte oppervlakte. Ten spyte van die vooruitgang in agronomiese praktyke en ontwikkeling van beter suikerriet variëteite is daar blykbaar geen waarneembare toename in suikerriet produktiwiteit oor die afgelope 20 jaar. Hierdie situasie het die vraag laat ontstaan of die gronde van Mauritius se kwaliteit nie onderworpe is aan ‘n daling, ‘n verskynsel wat ook elders voorkom weens die monoverbouing van suikerriet. Dit is in hierdie konteks dat die studie gedoen is om vas te stel of suikerriet produksie, en die implementering van gemeganiseerde praktyke ‘n negatiewe inpak op grondkwaliteit gehad het oor tyd.

Hierdie studie is tussen 2002 en 2006 op vyf suikerlandgoede, wat verteenwoordigend van die vyf hoof grondgroepe in Mauritius is, gedoen te wete die P, L, H, B en F groepe. Om die effek van suikerrietverbouing op grondkwaliteit vas te stel, is onversteurde gronde vergelyk met suikerrietgronde waaruit geen klippe verwyder en/of gelyk gemaak is nie. Laasgenoemde is dan vergelyk met suikerrietgronde waar sulke grondvoorbereidingspraktyke geïmplementeer is om die effekte van gemeganiseerde praktyke vas te stel. Om tydseffekte vas te stel, is ou suikerrietgronde (> 50 jaar) met nuwe suikerrietgronde (< 25 jaar) vergelyk in die P en L groepe, en vroeër gemeganiseerde gronde (> 10 jaar) met onlangse gemeganiseerde gronde (< 3 jaar) vergelyk in die P groep slegs. Die grondkwaliteitsparameters wat bepaal is, is biologies - organiese materiaal en mikrobiese biomassa; chemies - pH, katioonuitruilkapasiteit en uitruilbare katione; en fisies - deeltjiegrootteverspreiding, aggregaatgrootteverspreiding en stabiliteit teen water, brutodigtheid, waterhouvermoë, en gestabiliseerde waterinfiltrasietempo.

Suikerrietverbouing het positiewe en negatiewe effekte op grondkwaliteit gehad. Hierdie effekte is geassosieer met verbouingspraktyke, hoofsaaklik bewerking, organiese verbeteraars, bemesting en restebestuur. Sommige van die verskil met klimaat en gee daarom aanleiding tot kontrasterende resultate. Bogrond organiese materiaal het oor die algemeen afgeneem met gewasverbouing, waarskynlik as gevolg van blootstelling aan versnelde ontbinding na bewerking. Ondergrond organiese materiaal het toegeneem omdat bewerking lei tot die vermenging van bogrond met ondergrond. Bogrond mikrobiese biomassa het afgeneem met suikerrietverbouing omdat minder materiaal vir ontbinding beskikbaar was. Die hoër ondergrond organiese materiaalinhoud het ‘n positiewe effek op aggregaatstabiliteit gehad. Toevoeging van organiese verbeteraars tot die grond het oor die algemeen ‘n verbetering in pH, uitruilbare basisse en basisversadiging tot gevolg gehad. Versuring het ook in een geval voorgekom, waarskynlik as gevolg van stikstofbevattende bemestingstowwe. Bemesting het opbrengste verhoog en die het gelei tot ‘n hoër toevoeging van organiese materiaal tot die grond. Restebestuur tydens oes het ‘n belangrike rol gespeel in grondkwaliteit. Vooroes brand van reste het die toevoeging van koolstofbevattende materiaal tot die grond verlaag, terwyl die bewaring van reste wanneer groen suikerriet geoes word dit verhoog het.

Die implementering van gemeganiseerde praktyke het nie die chemiese grondkwaliteit geaffekteer nie. Grondorganiese materiaalinhoud het afgeneem met meganisasie in die droë sones as gevolg van verhoogde grondversteuring. Die belangrikste effekte van gemeganiseerde praktyke op die fisiese grondkwaliteit was verdigting in die bogrond weens gemeganiseerde oes. Tempo van waterinfiltrasie het afgeneem weens verlaagde bogrond makroporositeit terwyl waterhouvermoë toegeneem het.

Grondkwaliteit het nie sistematies verbeter of verswak met langtermyn gewasverbouing in die subhumiede gronde van Mauritius nie, en veranderinge was hoofsaaklik klein en varieerbaar. Nietemin, grondkwaliteit het met tyd afgeneem na die implementering van gemeganiseerde praktyke want groot hoeveelhede verbeteraars is aanvanklik toegevoeg tot die grond waarna uitputting daarvan toegelaat is. Die impak van gemeganiseerde praktyke op fisiese grondkwaliteit is waargeneem vanaf implementering en het nie met tyd na vore gekom nie.

Grondkwaliteit kan verbeter word deur die bogrond se organiese materiaalvlakke deur retensie van reste, toevoeging van groot hoeveelhede organiese afval en grondbemesting. Voorkoming is die beste strategie om verdigting teen te werk deur gebruik te maak van laedruk bande, gekombineerde bewerkingsoperasies en beheerde spoorverkeer.

Sleutelwoorde: gemeganiseerde praktyke, organiese materiaal, restebestuur, verdigting.

CHAPTER 1

INTRODUCTION

1.1 Background

Mauritius was discovered in September 1598 when a Dutch fleet under admiral Wybrandt van Warwijk sighted the uninhabited island in the course of a journey to India. The Dutch first settled the island in May 1638 and introduced sugar cane on 8 November 1639 when the "*Cappel*" brought the first plants from Batavia (North Coombes, 1993). The extracted juice was initially used for the production of a spirituous liquor called "arrack", and the first sugar proper was made in 1696.

The Dutch abandoned the island in 1710 and the French occupation started in 1721. By 1755, the French were producing enough sugar to meet the needs of the inhabitants of the colony, Réunion island and sailing ships that called at the harbour. In 1801, annual sugar production had reached 3000 t and "arrack" production 1400 kl. Cane was being cultivated over an area of 4220 ha and 60 mills were in operation.

The British captured the island in 1810 and a new impetus was given to cane cultivation. In 1825, sugar production had increased to 10 800 t and there were 10 975 ha under cane. By 1860, the island was producing 130 000 t of sugar annually. Significant technical progress was achieved subsequently with the coming into being of new institutions devoted to research and development in sugar cane. The *Station Agronomique* was set up in 1893, followed by the Department of Agriculture in 1913 and the Sugar Cane Research Station as from 1930. In 1953, all research pertaining to sugar cane was placed under the responsibility of the newly created Mauritius Sugar Industry Research Institute (MSIRI). The advent of these institutions has led to an island-wide increase in sugar production over the last century to reach a maximum of 718 000 t in 1973 from a cultivated area of 87 000 ha (PROSI, 1997).

1.2. Motivation

After reaching a peak of 87 000 ha in the mid-seventies, the area under cane has continually declined, at a rate of some 400 ha per year (Figure 1.1). The main reasons for this decrease were the land demand for urban development from an expanding population, the setting up of scattered factories in export processing zones and the need for additional infrastructure to accompany the development of the country in terms of roads, hospitals, sports facilities, traffic centres, etc. (Tyack, 1990).

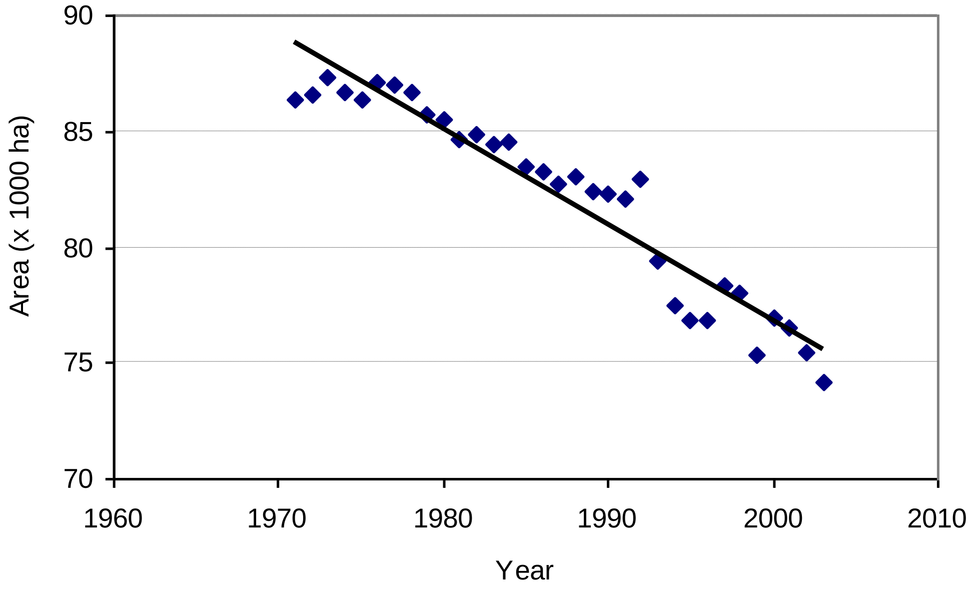


Figure 1.1 Evolution of area in Mauritius cultivated from 1971 until 2003 with sugar cane (Compiled from data in MSIRI Annual Reports, 1972 – 2004)

In the year 2002, sugar cane was grown on over some 75 000 ha (MSIRI, 2003), which represented about 90% of the total cultivated area in the country. Some 520 000 t of sugar were produced, with a productivity of 7.19 t ha^{-1}. This was much lower than the 8.89 t ha^{-1} of 1973 and the peak productivity of 9.10 t ha^{-1} recorded in 1986 (PROSI, 1997). Indeed, over the last twenty years there has been no apparent gain in productivity, the average value stagnating at around 8.0 t ha^{-1} with a slight declining trend, in spite of the introduction of new cane varieties and a constant input of inorganic fertilizers (Figure 1.2).

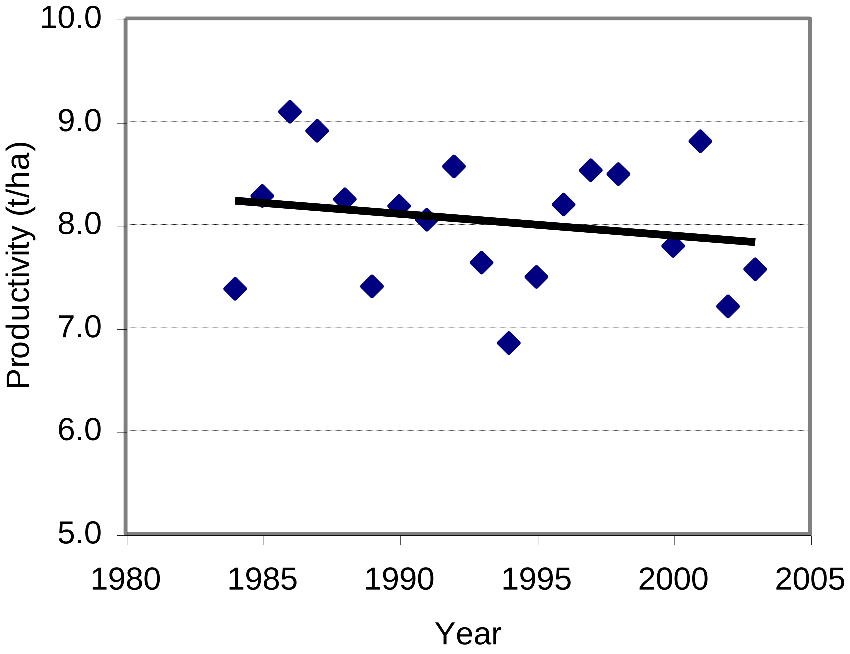


Figure 1.2 Evolution of sugar productivity in Mauritius from 1984 until 2003, excluding the drought year 1999 and cyclone years 1994 and 2002 (Compiled from data in MSIRI Annual Reports, 1985 – 2004)

Cane cultivation in Mauritius is similar to other countries in that it is grown with little or no break crop in between replantings. There is very little crop rotation in the cane lands and in most cases, the cane is grown continuously for long periods of time. It is ratooned, i.e. allowed to regrow repeatedly after the harvest of the plant cane until the yield has decreased to such an extent that replanting is necessary, seven ratoons being generally the optimal crop cycle. Regular replanting is needed as the yield gradually decreases following repeated harvest of the shoots produced by regrowth from the existing cane stools, a natural phenomenon called ratoon decline (Shrivastava *et al.*, 1992). This practice of allowing canes to ratoon is a very old one, which existed even as early as 1838 (North Coombes, 1993) when replanting was done every five years.

Sugar cane cultivation in Mauritius is done under monocropping, with the soil being tilled once every eight years when replanting. As such, in addition to the yield losses caused by ratoon decline, the crop also suffers from yield decline, a loss of productive capacity of sugar cane growing soils under long-term monoculture (Garside *et al*., 2001). Coleman (1974) reviewed research conducted over a ten-year period in the USA on the "variety decline of sugar cane" phenomenon, which was studied from agronomic, pathological and physiological viewpoints. In agronomic terms, it had been demonstrated that it was difficult to find a specific cause for long-term yield reduction. Very often, differences might be caused by climatic or environmental conditions, which would override a specific cause. In pathological terms, it was shown that soil micro-organisms did reduce yield under certain conditions, with environmental conditions playing a role in the evolution of the microbial population. However, the evidence was not over a long enough period to implicate any specific organism, and additional studies were needed to confirm this finding. As far as physiological studies were concerned, there was no obvious basis to blame yield decline on photosynthetic differences. In the end, Coleman (1974) considered that inconclusive results were obtained from these attempts at documenting yield decline resulting from monoculture.

The yield decline issue was given new impetus in Australia as from 1993 through the establishment of a joint venture to research the subject (Garside, 1997). Emphasis in this new approach was on the ability of the soil to sustain sugar cane production. Several studies have been implemented within this initiative to study different soil-related aspects of the problem. These have demonstrated that the productive capacity of the soils was reduced by sugar cane monoculture (Garside, 1997; Garside *et al*., 2001).

Holt and Mayer (1998) found that reduced levels of soil microbial biomass with long-term sugar cane monoculture could also contribute to yield decline. Garside *et al.* (2002) obtained better cane yields with fumigation using fungicide alone and together with nematicide when compared to untreated controls. For their part, Pankhurst *et al.* (2003) have identified several soil organisms that contribute to yield decline, including a fungal root pathogen and the lesion nematode. They also demonstrated that different rotation breaks (sown pasture, alternate crops, bare fallow) would reduce populations of known soil biota and significantly increase the yield of the succeeding cane crop.

Results from physico-chemical studies on soils were less conclusive. Bramley *et al.* (1996) did not find any consistent effect of time under sugar cane monoculture on soil chemical properties, but some marked effects consistent with soil acidification were noted. For their part, McGarry and Bristow (2001) found some degree of physical degradation with old sugar cane land, mainly in terms of increased bulk density and lower available water.

Apart from Australia, yield decline under sugar cane monoculture has also been studied in other countries. For instance, in South Africa, Meyer and Van Antwerpen (2001) have reviewed the yield productivity plateau of the local sugar industry with reference to soil quality. They concluded that continuous cropping with sugar cane had adversely affected soil productivity, this degradation being attributable to increased soil acidification, loss of soil organic matter and an imbalance in soil biota. A similar situation has occurred in Papua New Guinea where Hartemink (1998a) found a marked decline in soil fertility under sugar cane monocropping, even though nutrient levels remained favourable for sugar cane cultivation. In this case, there was a drop in pH accompanied by a decrease in cation exchange capacity (CEC), exchangeable potassium, organic carbon and total nitrogen.

Such results from different sugar-producing countries raise the question as to whether sugar cane production can be maintained at its current level in Mauritius with the existing cultural practices. Wong You Cheong and Chan (1977) had already undertaken preliminary studies on changes in physical and chemical properties of the main soils of Mauritius following long term cultivation of sugar cane. They have found a decrease in soil pH, organic matter content, exchangeable calcium and percentage base saturation. On the physical side, they measured a decrease in aggregate stability, but did not find any definite trend in terms of bulk density, plant available water or clay contents. There was thus a certain degree of soil degradation even in those days when, apart from soil tillage, most cultural operations were manually executed.

Soil degradation is likely to be exacerbated by the increasing use of machinery. Mechanized harvesting is gaining importance in Mauritius, rising from 1139 ha (1.5% of total area harvested) in 1990 to 5028 ha (7.2% of total area harvested) in 1995 and reaching 13 742 ha (19.0% of total area harvested) in 2002 (MSIRI, 2003). However, further increases in the mechanically harvested area are hampered in several regions by the presence of rocks and stones that damage harvester blades, and by inappropriate field shapes and topography. These problems are being addressed by large scale derocking, which is defined as rock removal using mechanical means, and by land preparation. Fields need to be re-sized, leveled and derocked to achieve these objectives. Eventually, only fields that are relatively flat and rock-free, with long sugar cane rows, will be economically viable for sugar cane production.

So far, more than 50% of rocky land has undergone some form of derocking and it is estimated that some 58 to 101 million t of rocks can still be raked out of those rocky soils that are yet to be derocked (Jhoty and Ramsamy, 2003). While the adoption of such measures is undoubtedly essential to achieve the goal of complete mechanization of cultural operations, and hence lowering of production costs, their effects on soil remain unknown. For the industry to maintain its production in the long-term, it is essential that the effects of all these new practices on soil properties be established, with particular attention to soil quality, i.e. to the ability of the soil to meet its various functions, such as supplying a medium for plant growth, controlling water flow in the environment and acting as an environmental filter.

1.3 Objectives

In view of the observations on the issue of yield decline with sugar cane monoculture reported in the literature, and its possible links with degradation of soil properties, a study was initiated at the MSIRI to determine the effects of sugar cane cropping and the adoption of mechanized practices on soil quality in Mauritius. This project has the following objectives:

1. To establish the effects of manual sugar cane production practices on some biological, chemical and physical soil quality parameters of the island's five major soil groups using pristine soils as a reference.

2. To establish the effects of mechanized sugar cane production practices on some biological, chemical and physical soil quality parameters of the island's five major soil groups using sugar cane soils that have not been subjected to these practices as a reference.

3. To establish the effects of time under manual sugar cane production practices on some biological, chemical and physical soil quality parameters of two major soil groups on the island.

4. To establish the effects of time under mechanized sugar cane production practices on some biological, chemical and physical soil quality parameters of one major soil group on the island.

5. To formulate recommendations to maintain and restore soil quality, and to identify avenues for future research in this field.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Modern-day agriculture relies heavily on external inputs, particularly non-renewable fossil fuels, for the synthesis of fertilizers and pesticides, and for the energy needs of tillage, harvest and other cultural operations. Such a heavy reliance on non-renewable resources raises questions about the long-term sustainability of agriculture (Doran *et al*., 1996). There is an increasing concern about the sustainability of the energy- and chemically- intensive industrial agricultural model, as soil degradation has often accompanied agricultural expansion (Lal, 2001). This has led to renewed interest in evaluating the soil resource, this interest being further stimulated by an increasing awareness that soil is a critically important component of the Earth's biosphere, functioning not only in the production of food and fibre, but also in the maintenance of local, regional and global environmental quality. In this respect, a new concept was needed to evaluate the quality of the soil resource. Soil quality can be conceptualized as a three-legged stool, the function and balance of which requires an integration of three major components – sustainable biological productivity; environmental quality; and plant and animal health (Karlen *et al*., 1997). As far as sugar industries are concerned, the relevance of soil quality indicators to sugar producing soils needs to be considered, and the use of such indicators has been advocated to further investigate soil degradation and sustainability under continuous sugar cane producing conditions (Haynes, 1997).

In this review, the development of the soil quality concept will be explored through time and the contributions of different workers to its refinement will be presented. The current ideas on soil quality will be examined and the term will be differentiated from the term "soil health". The concept also has its detractors and some of their arguments will be assessed. After defining the concept, the various physical, chemical and biological soil quality indicators will be detailed and the minimum data set (MDS) concept examined. The major part of this literature review will then focus on the research work that studied the effects of sugar cane production practices on the quality of soils in different cane-growing countries. Finally, some conclusions will be drawn from the current state of knowledge on the subject.

2.2 The concept of soil quality

2.2.1 Development of the concept

The foundation for the development of the concept of soil quality is, according to the Soil Quality Institute (1996), found in the views put forward by Leopold (1933). He was among the first scientists to envision land conservation, discussing the fundamental concepts of conservation and laying down the theoretical foundation for the concept of soil quality. In more recent times, Warkentin and Fletcher (1977) further developed these ideas, putting forward a holistic approach to soil, whereby they postulated that due consideration should be given to its possible multiple uses, even in intensive agriculture. They concluded that the optimum had to be found between the two most important uses of soil, namely food production and recycling of organic materials.

The broader concept of soil quality was effectively introduced into the literature in the mid to late 1980's, when several reports and books brought attention to the increasing degradation of agricultural soil resources and its implications for sustainable agriculture and environmental health (Karlen *et al*., 2001). It was in the 1990’s that the concept gradually evolved and became formalized in its present form. Soil quality was viewed and described from different perspectives, and the current theory and concepts were established. The increased emphasis on sustainable land use during that period has been crucial in this evolution. In this context, Larson and Pierce (1991) expressed the view that the soil is in a continually changing, dynamic situation, where its quality would be either degrading, sustaining or aggrading, in processes that are driven by both natural and managed environments. Consequently, they argued that the quality of a soil is largely defined by soil function and that it represents a composite of the physical, chemical, and biological properties that allow it to carry out such diverse functions as providing a medium for plant growth, regulating and partitioning water flow through the environment, and serving as an environmental filter. Parr *et al*. (1992), for their part, thought that there are various properties that interact in complex ways to determine a soil's potential fitness for sustained crop production. In their view, the soil quality concept had to be broadened from its initial soil productivity viewpoint to include attributes of food safety and quality, human and animal health, and environmental quality. Warkentin (1995) described soil quality from an ecological perspective, asserting that it should be seen in terms of the optimum functioning of the soil in an ecosystem. In his opinion, the roles of soil in ecosystem processes, and the characteristics that make it particularly suitable to carry out these roles, should form the basis for evaluating soil quality. For their part, Kennedy and Papendick (1995) considered that the microbial status of a soil would be a better and more sensitive indicator of its quality than other soil properties since the microbial community is continually adapting to the environment, and changing faster than other soil characteristics. Karlen *et al*. (1997) tried to integrate these various perceptions of the concept in terms of its three major components, namely sustained biological productivity, environmental quality, and plant and animal health, and stressed that multiple soil uses had to be balanced against goals for environmental quality. They refocused the issue on the primary purpose for assessing soil quality, which is to use it as a tool for evaluating the sustainability of various soil management practices.

In recent years, the emphasis has shifted towards measuring soil quality using methodologies that would be comparable, and acceptable to the farming community. Thus, Nortcliff (2002) stressed that any index of soil quality had to consider soil function, and these are varied and often complex. Chosen indicators of soil function must be measured in a standardized way to be replicable and comparable, which would be possible only through co-operation among interested parties. Two areas of emphasis, namely education and assessment, have been recognized as integral parts of the concept (Karlen *et al*., 2003). For Doran (2002), the challenge lies in taking the right approach to translate science into practice. This requires the involvement of growers in the development of a soil quality index that would be acceptable to its target audience, as attempted by Andrews *et al*. (2003).

2.2.2 Soil quality and soil health

There has been a certain degree of confusion between the terms soil quality and soil health. For Harris *et al*. (1996), the two terms could be interchangeably and functionally defined as "the fitness of soil to carry out biological production and environmental protection functions within specified land use, landscape and climate boundaries". Doran (2002) used the two terms in combination as he considered them to have a similar meaning, even though scientists generally prefer to use "soil quality" while producers prefer "soil health" (Doran *et al*., 1996). Scientists prefer soil quality since it implies quantifiable parameters of its physical, chemical and biological properties. On the other hand, producers prefer soil health since it portrays soil as a living, dynamic organism that functions holistically rather than as an inanimate mixture of sand, silt and clay.

Even though the two terms have similar meanings, there are enough differences to justify that they ought to be differentiated (Karlen *et al*., 1997). Farmers prefer the more integrative soil health term as they could characterize it using indicators of both soil and non-soil target systems (Romig *et al*., 1996). Thus, the farmers' diagnosis of a soil's condition primarily uses qualitative or sensory means in addition to quantitative data. Soil health is therefore more of a qualitative term, characterized at the farmers' level by descriptive and qualitative properties using direct value judgments, viz. unhealthy versus healthy. In contrast, the term soil quality has greater appeal to the scientific community since it implies that parameters defining it are measurable and quantifiable and as a result, scientific literature refers essentially to soil quality rather than soil health.

2.2.3 Opposition to the concept

Criticisms and reservations have been expressed about the concept of soil quality. Sojka and Upchurch (1999) challenged the applicability of the concept in integrating the simultaneity of diverse and often conflicting functions of the soil. They stated their concern that a single soil quality index was unattainable and that having individual indices for all soils and circumstances would be unachievable, complex and completely confusing. They further argued that, while air and water quality could be defined, soil quality could not be defined since, as opposed to air and water, there is no such thing as pure soil. Sojka *et al*. (2003) further developed these views as they considered the definition of soil quality to be elusive and value-laden. They believed that the concept carried policy overtones, led to regional and taxonomic biases, failed to reconcile conceptual contradictions, and that its ambiguous definitions were confounded by countless circumstance-specific, function-dependent scenarios. They also argued that it did not offer practical means to manage conflicting soil management requirements for the multiple functions of soil that it acknowledges to occur simultaneously. Sojka *et al*. (2003) expressed their reluctance to endorse the holistic approach advocated by the soil quality concept in replacing the traditional approach of specific problem solving used in soil science. They concluded by suggesting that emphasis should be laid on quality soil management rather than management of soil quality as a professional and scientific goal for all scientists. For their part, Letey *et al*. (2003) also opposed the soil quality concept, but suggested that, if the concept were to be retained, soil use should be the criteria for attribute evaluation, rather than soil function or capacity.

2.2.4 Soil quality definition

As reviewed by Doran and Parkin (1994), several workers have tried to find a correct definition for the concept of soil quality, and the common factor in all these definitions was the “capacity of the soil to function effectively at present and in the future”. Based on these previous definitions, they concluded that soil quality should be defined as “The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health”. In view of the various definitions put forward in the literature, the ad hoc committee S-581 set up by the Soil Science Society of America has come up with the following definition for soil quality (Karlen *et al*., 1997): "The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support animal health and habitation".

2.2.5 Soil quality indicators

While putting forward its theory and concepts, Larson and Pierce (1991) were already addressing issues of ways and means of evaluating soil quality and its change due to management practices. They believed that indicators of soil quality and its changes should reflect the soil's ability to perform the three critical functions of providing a medium for plant growth, controlling water movement through the environment and acting as an environmental filter. This ability to perform these three functions could be measured by means of a minimum data set (MDS) incorporating different selected soil parameters, such as nutrient availability, total and labile organic carbon, texture, plant available water capacity, structure, strength, maximum rooting depth, pH, and electrolytic conductivity.

Doran and Parkin (1996) proposed an upgraded MDS for screening the condition, quality and health of soil, incorporating chosen physical, chemical and biological indicators. This new MDS included additional soil biological data such as microbial biomass carbon and nitrogen, potentially mineralizable nitrogen (anaerobic incubation), and soil respiration, water content and temperature. Karlen *et al*. (1997) expanded on this list of selected soil quality indicators and included soil aggregation as a new indicator (Table 2.1). Most of these parameters have stood the test of time and are still relevant. They constitute the core of the work that has been done on the changes in soil quality that take place as a result of sugar cane cultivation.

Table 2.1. Selected indicators of soil quality and some processes they impact (Karlen *et al.*, 1997)

Measurement	**Process affected**
Organic matter	Nutrient cycling, pesticide and water retention, soil structure
Infiltration	Runoff and leaching potential, plant water use efficiency, erosion potential
Aggregation	Soil structure, erosion resistance, crop emergence, infiltration
pH	Nutrient availability, pesticide absorption and mobility
Microbial biomass	Biological activity, nutrient cycling, capacity to degrade pesticides
Forms of N	Availability to crops, leaching potential, mineralization and immobilization rates
Bulk density	Plant root penetration, water- and air-filled pore space, biological activity
Topsoil depth	Rooting volume for crop production, water and nutrient availability
Conductivity or salinity	Water infiltration, crop growth, soil structure
Available nutrients	Capacity to support crop growth, environmental hazard

2.3 Sugar cane production and soil quality

2.3.1 General

Determining the long-term effects of sugar cane cultivation on soil quality is difficult as it is not possible to have a direct basis for comparison, mainly because the initial properties of the soil prior to cane cultivation are not known. Had it been otherwise, comparison could have been made between the initial "before cane" status and the subsequent "after cane" status. Only a few studies have been made in this sort of situation, but these were for relatively short periods. For instance, changes in the properties of three Oxisols were monitored annually in

Fiji for six years, all three sites having initially been under native vegetation prior to the development of the sugar cane project (Masilaca *et al*., 1986). Most of the time, however, the effects of sugar cane cultivation on soil quality have been determined in a less direct manner, with the properties of soils under sugar cane being compared to those of adjacent native (uncultivated) zones, as in e.g. Van Antwerpen and Meyer (1996) and Garside *et al*. (1997).

These studies have shown that sugar cane cultivation had variable effects on soil quality. Most of the time, the effects were perceived to be negative. Thus, throughout the sugar cane producing areas of the world, it was common to find a diminution in soil quality attributable to sugar cane production (Haynes and Hamilton, 1999). Soil quality research work from various sugar cane producing regions, such as Fiji, Swaziland, Papua New Guinea, Australia and South Africa has shown that the conversion of virgin land to sugar cane production resulted in a progressive loss in soil quality. The main symptoms of this soil degradation were loss of soil organic matter, soil acidification and/or salinisation, and compaction of the inter-row. This general soil degradation has been confirmed by the research work dedicated to yield decline in Australia by the Sugar Yield Decline Joint Venture, and in South Africa by SASEX. Both research groups have shown that land cultivated to sugar cane was degraded relative to virgin land since soil chemical, physical and biological properties had significantly changed for the worse under continuous sugar cane production (Meyer and Van Antwerpen, 2001).

However, there were instances where the effects of sugar cane cultivation were found not to be detrimental to the soil. In their study over three climatically different zones in North Queensland, Bramley *et al*. (1996) found no evidence of a consistent effect of time under sugar cane monoculture on soil chemical properties, even if the results did suggest a general decline in soil fertility over time. In the Goondi mill area of Queensland, McLean (1975) found only small changes in physical and chemical properties associated with the long-term (almost one century) cultivation and growth of sugar cane under the monocultural system. In Bundaberg, Queensland, McGarry *et al*. (1996) concluded that sugar cane cultivation had resulted in favourable changes in several soil physical and chemical properties, such as improvements in bulk density and increase in organic matter content, even though these had not led to improved aggregate stability or increased microbial biomass.

The various studies aimed at determining the effects of sugar cane cultivation on soil quality have concentrated mostly on certain specific parameters. Two biological indicators have received specific attention, namely soil organic matter and microbial biomass. However, most of the work has been done on soil chemical properties, specifically soil acidification, cation exchange capacity, available nutrients such as calcium, magnesium, potassium and phosphorus, and salinity. A soil physical quality indicator that has received specific attention turned out to be soil compaction in the inter-rows. The stabilized infiltration rate of the soil, its plant available water and texture, and the stability of aggregates to water were the other physical indicators that have been studied.

2.3.2 Biological parameters

2.3.2.1 Organic matter

An initial decrease in soil organic matter (SOM) has been commonly observed when virgin land was put under sugar cane (Haynes and Hamilton, 1999). This decrease was most marked in the topsoil, i.e. in the top 10 to 15 cm, as expressed by changes in organic carbon and total nitrogen in the soil profile (Figure 2.1). The extent of this reduction varied according to sites and soil types. However, changes in SOM content did not follow the same trend in the subsoil. At greater depths, SOM content tended to decrease but not to a significant degree. Under certain circumstances, there were even cases where SOM content increased in the subsoil.

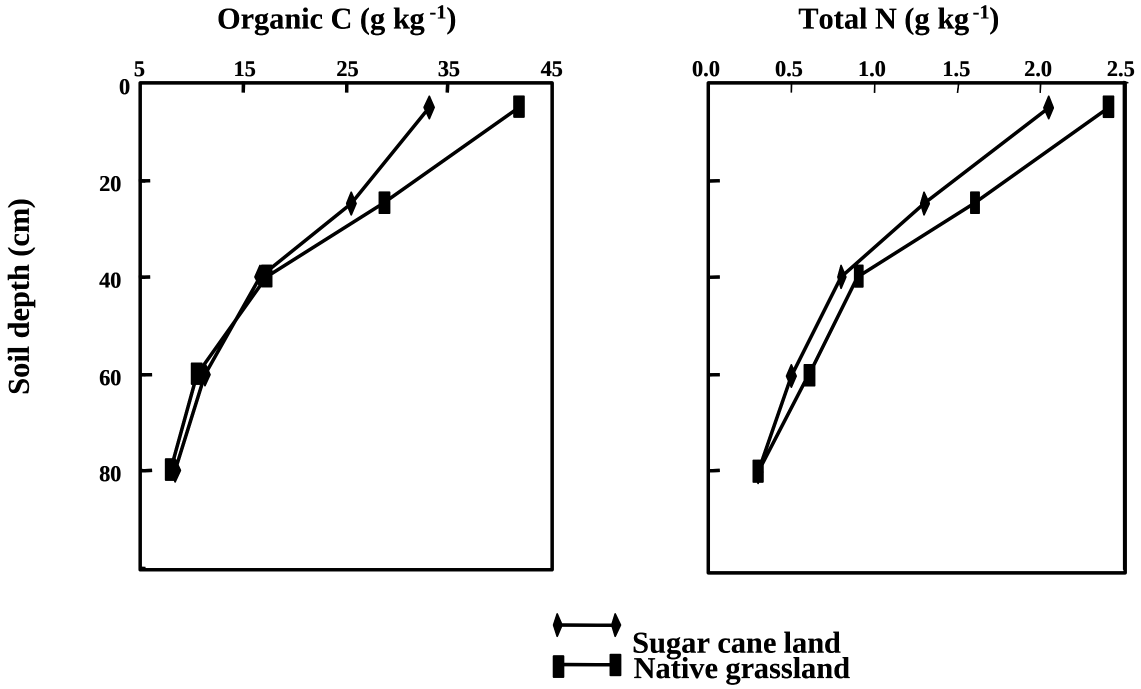


Figure 2.1 Decrease of soil organic matter content observed seven years after native grassland was converted to sugar cane land (redrawn from Haynes and Hamilton, 1999).

There are other examples to illustrate that there is a decrease in SOM content in the topsoil following cane cultivation. For instance, Van Antwerpen and Meyer (1996) studied 29 sites in the KwaZulu–Natal province of South Africa under three soil types and observed that, at all sites, there was a significant decline in the SOM content of the upper layer following the introduction of sugar cane. In the North East Swaziland lowveld, Henry and Ellis (1996) studied two soil types under sugar cane and found that cropping resulted in a decrease of about 8% in organic carbon and 26% in total nitrogen in the top 15 cm layer of the two soils. In Queensland, Australia, McGarry *et al*. (1996) found an organic carbon content of about 1.5% in the top 5 cm of an uncultivated soil as opposed to about 1.0% in the soil from a cane row. However, not all studies have concluded that SOM content would decrease when virgin land is put under sugar cane. Thus, in North Queensland, Bramley *et al*. (1996) found that the organic carbon content of a soil from “old” cane land was in the order of 2.8% compared to some 1.6% for a “new” cane land soil.

Even though SOM content generally decreased with the introduction of sugar cane, this decline did not occur at a constant rate. This decrease occurred rapidly just after sugar cane introduction, slowed down after a few years, before levelling out to a new equilibrium when the SOM content remained constant. This trend is best illustrated by Dominy *et al*. (2001), who found that soil organic carbon content declined rapidly in the first ten years after putting a virgin soil under sugar cane and then stabilized to a new equilibrium level after thirty years in the low clay soil and fifty years in the high clay soil (Figure 2.2).

The rate of decline in SOM content was measured by Hartemink (1998b) in Papua New Guinea between 1979 and 1996 for two soil types that were under rainfed sugar cane production. In that relatively short interval, the organic carbon level declined by about 40% from 5.5% to 3.1%, giving an average decline rate of 0.14% per year. A similar exercise was undertaken for a long-term situation in two climatically different KwaZulu-Natal dryland regions (Qongqo and Van Antwerpen, 2000). It was found that SOM content decreased from 4.7% to 2.9% in 50 years (average loss rate of 0.04% per year) at the South Coast, and from 6.1% to 5.8% in 30 years (loss rate of 0.01% per year) in the Midlands. The data from Dominy *et al*. (2001) also indicated that the initial SOM decline rate was less marked for soils with higher clay contents, since SOM decreased at 0.13% per year in the soil with high clay compared to 0.30% per year for the soil with low clay, over the first ten years after sugar cane introduction. However, in the long-term, the protective effect of clay was no longer obvious and SOM decline rate stabilized to a much lower rate of 0.02% per year for both soils.

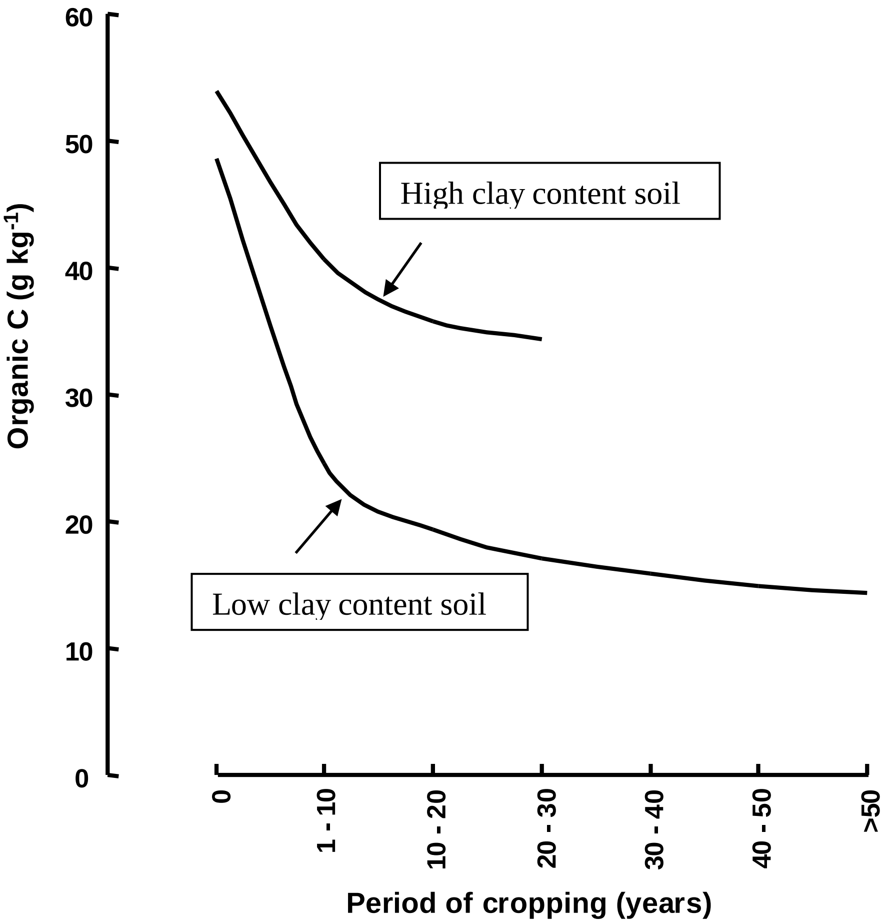


Figure 2.2 Decline of soil organic carbon content through time on account of sugar cane production in South Africa (redrawn from Dominy *et al*., 2001).

In addition to the determination of decline rate in SOM content, another aspect that has been studied is the fate of its various components. Skjemstad *et al*. (1999) conducted a study on three soil types in Queensland, comparing “old” to “new” cane lands. They showed that cane production resulted in very little change in the overall chemistry of soil organic carbon. In the whole soil profile, total organic carbon did not decline with increasing time under cane production, even though there was probably some movement of carbon down the profile. The proportion of light fraction organic carbon, defined as having a density lower than 1.6 g cm^{-3}, remained relatively constant irrespective of cultivation history. Generally, this fraction decreased with increasing depth but there were no obvious and consistent differences between virgin/new sites and old sites. On the other hand, inert organic matter, viz. charcoal had accumulated in the profile as a result of annual cane burning. This increase had possibly masked the losses in the more labile forms of carbon that were important for maintaining adequate soil structure and fertility. Thus, while the total organic C content might be constant or even increase, the relative contribution of different C pools might change. This could explain why the soil structure might decline even though total organic carbon content remained unchanged.

The possibility that organic carbon originating from surface horizons could move down the profile, and thus increase the SOM content of deeper layers, is supported by data from Masilaca *et al*. (1986), who found an increase in organic C in the 30-40 cm layer. In this case, the downward movement of organic C could be ascribed to the secondary effects of ripping and rotovating during the initial land preparation. For their part, McGarry *et al*. (1996) found that a sugar cane cultivated site had almost twice the amount of organic carbon between 5 and 45 cm depth, compared to an uncultivated one. Below the 45 cm depth, there was no noteworthy difference. In this case, the difference was explained by a two-year break in the cultivated site, during which the site was planted with peanuts, followed by tomatoes and zucchinis. After these two years, the site had been ploughed to a depth of 40 cm prior to replanting sugar cane, and the residues of the break crops could have helped to increase the OM content in the subsoil.

However, the evolution of OM content in the subsoil of sugar cane fields is not as clear-cut as for the topsoil. It has also been found in other studies that OM content either remained unchanged or decreased in the subsoil. Van Antwerpen and Meyer (1996), for example, found that OM content was lower in the subsoil of a cane planted field compared to one under native vegetation. However, the difference in organic carbon between the two situations diminished with increasing depth. For their part, Henry and Ellis (1996) found that there was no difference between virgin and cane soils deeper down in the soil profile of an Oxisol, but found marked reductions over the entire sampling depth in a duplex soil, measured at 22% for the 15-30 cm layer and 50% for the 45-60 cm layer.

The changes in SOM content throughout the profile have been attributed to various causes by Dominy *et al*. (2001) who put forward three main reasons: (i) a lower return of carbonaceous residues to the soil; (ii) enhanced aggregate disruption and exposure of physically-protected organic material to microbial action following cultivation; and (iii) enhanced rates of decomposition due to more favourable conditions. Another possible reason was put forward by Masilaca *et al*. (1986), who noted that the soil organic carbon content declined in the early months following planting and suggested that it was an artifact caused by mixing of topsoil and subsoil during land preparation.

A few practices play an important role in arresting the degradation in SOM content. The change from cane burning to green harvesting and trash retention has been identified as an essential evolution in this respect. Wood (1985) conducted a study at 19 sites in the Herbert Valley of North Queensland and found a substantial decline in SOM content of the top 10 cm, where the organic carbon content was reduced by more than 50%. A further 20% reduction was noted in the next 10 cm layer. Wood (1985) concluded that this substantial decline was due to the removal of crop residues associated with the pre- and post-harvest burning of trash. On the other hand, Bramley *et al*. (1996) compared “old” to “new” sugar cane land in North Queensland but found no marked difference in soil organic carbon content, except at one site where the organic carbon content in the “old” land was higher in the top 5-cm layer, but lower throughout the rest of the profile. As opposed to the situation investigated by Wood (1985), the higher SOM content in the study of Bramley *et al*. (1996) could be ascribed to the beneficial effect of green cane harvesting and trash blanketing system. The work by Graham *et al*. (1999) confirmed that trash blanketing has beneficial effects on organic carbon content in the topsoil (Figure 2.3). Soil under trash blanketing had a higher organic carbon level than cane soil harvested under burnt condition, and even higher than virgin soil. Thus, it appears that long-term sugar cane production with trash retention has actually led to an increased SOM content, while burning reduced SOM content.

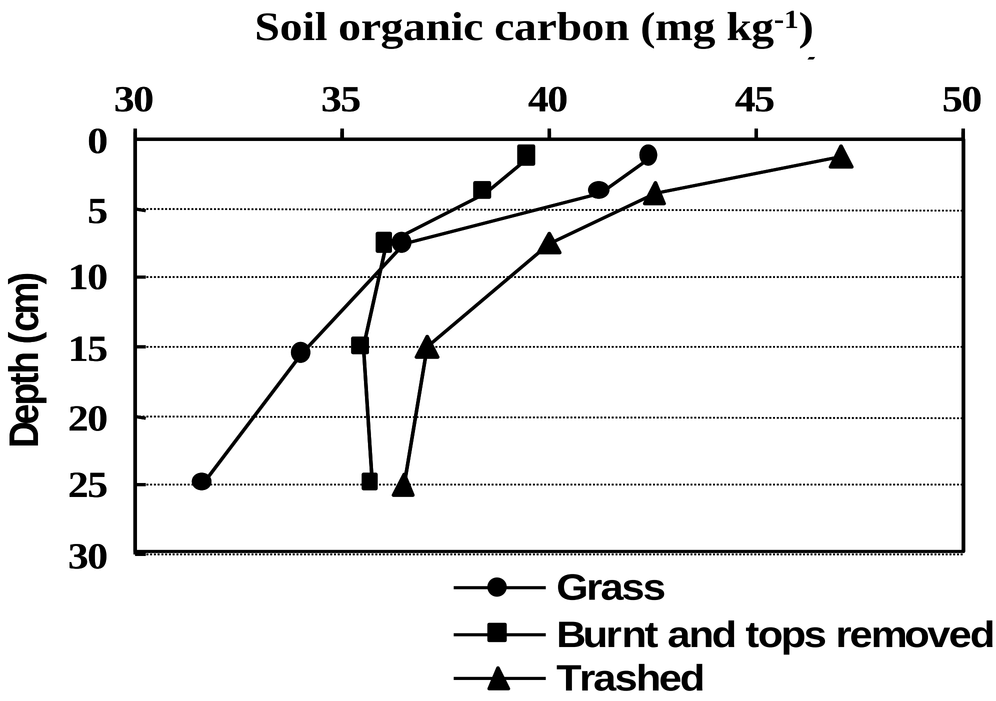


Figure 2.3 Effect of sugar cane trash management on soil organic carbon content in South Africa (compiled from Graham *et al*., 1999).

Further confirmation of the beneficial effects of green harvesting came from Skjemstad *et al*. (1999) who noted that even in situations where total organic carbon did decline, the practice of cane trashing had maintained the light carbon fraction in proportion to total organic carbon in soil.

2.3.2.2 Microbial biomass

A marked decline in soil microbial biomass has been observed under sugar cane cultivation when compared to virgin sites. Thus, declines in microbial biomass carbon of 32 and 83% have been measured in the 0 to 5 cm and 15 to 20 cm layers respectively when a site cultivated with sugar cane was compared to an uncultivated one (McGarry *et al*., 1996). In fact, the decrease in soil microbial biomass associated with cane production has been found to follow the same trend as for organic carbon, except that this decrease was more pronounced (Dominy *et al.*, 2001). As with SOM content, microbial biomass carbon decreased rapidly for the first ten years after the introduction of sugar cane, and stabilized thereafter at a new equilibrium level within twenty years (Figure 2.4). The microbial quotient (microbial biomass carbon as a percentage of total soil organic carbon) stood initially at 2.60%, but decreased to 1.37% for a Ferrasol and 1.46% for a Cambisol under the effect of sugar cane production. However, the microbial biomass carbon content was more affected than SOM content depth-wise, since it was lower in the top 25 cm of the soil profile (Figure 2.5).

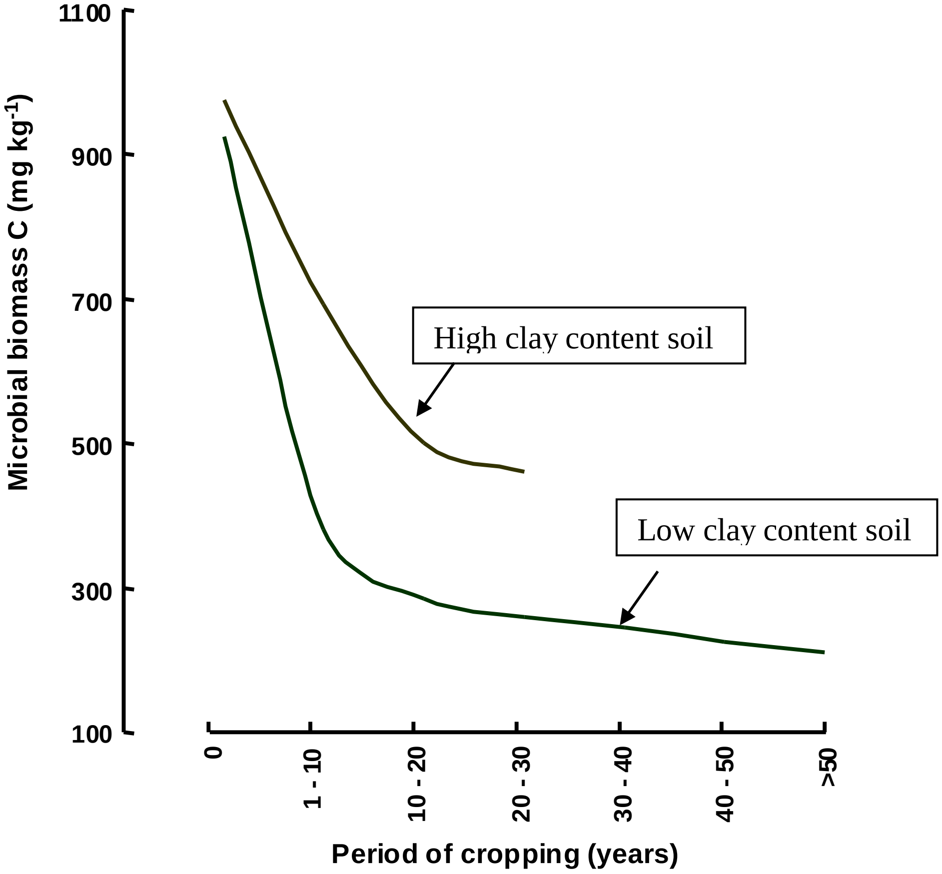


Figure 2.4 Change in soil microbial biomass carbon as a result of sugar cane production in South Africa (redrawn from Dominy *et al.*, 2001).

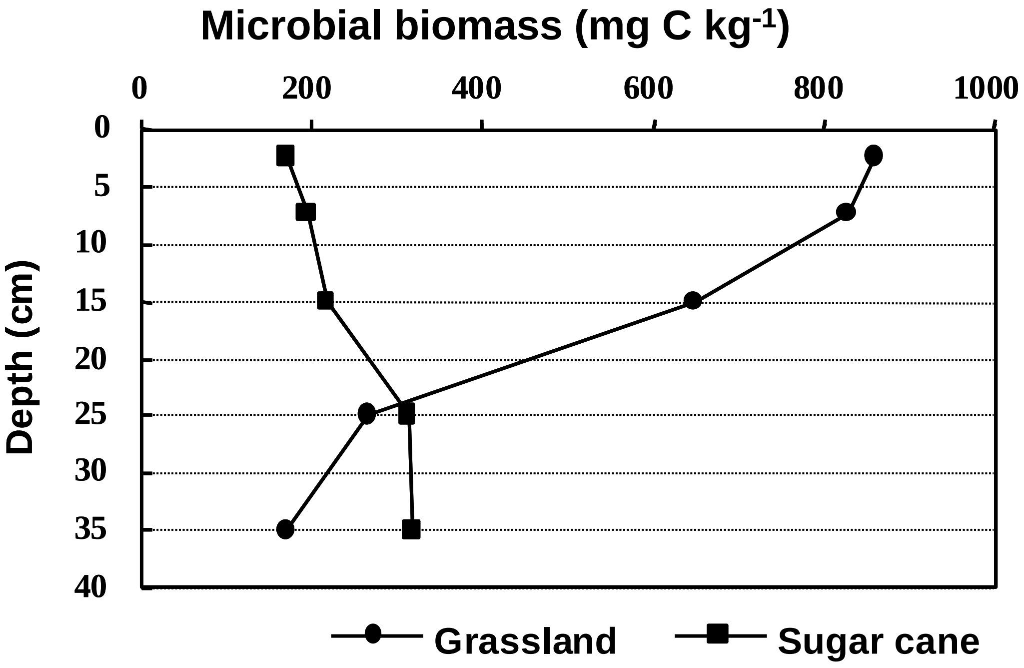


Figure 2.5 Microbial biomass carbon recorded in South African soil profiles with sugar cane and grassland (adapted from Dominy *et al*., 2001).

The depressing effect of sugar cane cultivation on soil microbial biomass contents can be reversed under specific circumstances. In a study comparing native soil with sugar cane soil under contrasting harvesting conditions, Graham *et al*. (1999) have demonstrated that even though the virgin site had a higher microbial biomass carbon content throughout the profile than a sugar cane plot that was burnt prior to harvest, it had a lower content than another plot where no burning took place and where trash was conserved at harvest (Figure 2.6). This observation was explained by the fact that, with annual fertilizer applications, there was an increased return of organic residues to the soil in the form of decaying roots, litter trash and tops. This increased return had led to an increase in soil microbial population in response to the higher amount of residues available for decomposition. In contrast, there was no such effect in cases where the residues were burnt prior to harvest.

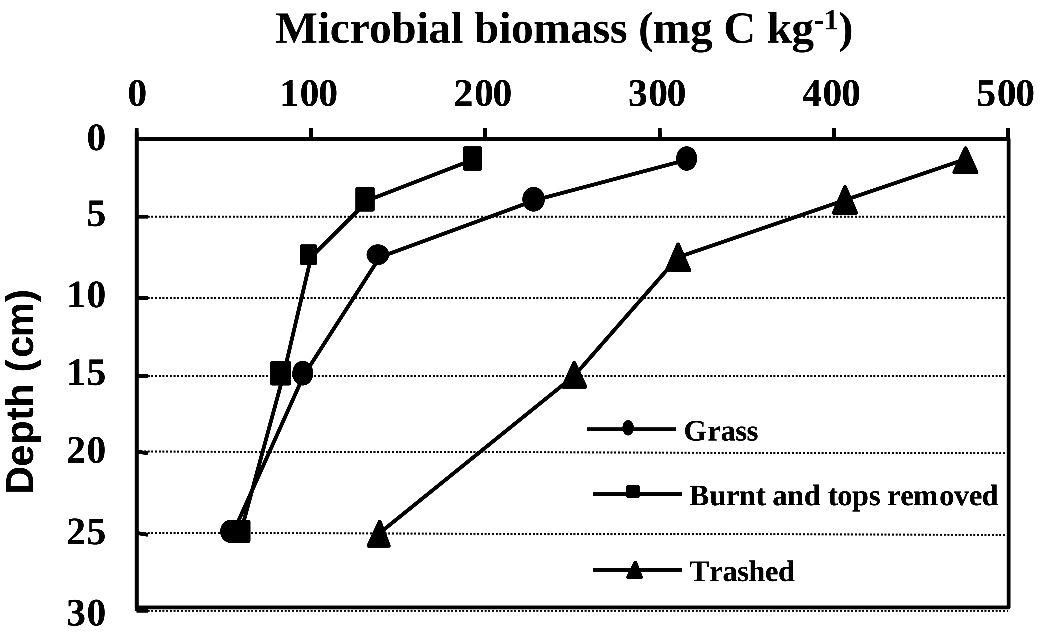


Figure 2.6 Microbial biomass carbon recorded in soil profiles with sugar cane subjected to different harvesting procedures (adapted from Graham *et al*., 1999).

2.3.3 Chemical properties

2.3.3.1 pH

Soils under sugar cane generally have a lower pH than those under native vegetation (Haynes and Hamilton, 1999). This decrease in soil pH can be accompanied by a concurrent increase in exchangeable aluminium levels (Wong You Cheong and Chan, 1977). However, new sugar cane cultivation does not automatically mean soil acidification. For instance, Van Antwerpen and Meyer (1996) observed that there was no significant difference in pH between virgin and cane soils, even though cultivation led to a decrease of the order of 0.26 pH units under dryland conditions, and an increase of 0.14 pH units under irrigated conditions. For their part, Masilaca *et al*. (1986) did not find any clear trend in the evolution of topsoil pH, which fell immediately after planting, but seemed to rise again in the longer term. There could also be an effect in relation to soil depth, as in the case where cropping under sugar cane led to a slight acidification of the topsoil, whereas the converse was true of the subsoil (Henry and Ellis, 1996). This observation was explained by the fact that bases could have been leached from the topsoil into the subsoil as a result of irrigation.

Three main causes have been identified for the accelerated acidification of soils under sugar cane cultivation (Meyer *et al*., 1998): (i) oxidation of ammoniacal fertilizers to nitric acid; (ii) mineralization of organic matter; and (iii) leaching of basic cations from soil. However, the detrimental effect of ammoniacal fertilizers, particularly ammonium sulphate, is regarded as the most important (Wood, 1965; McLean, 1975; Wood, 1985). In contrast, the acidifying effect of urea, which is more commonly used than ammonium sulphate, is 50% less than the latter since its net potential acidity is 0.072 compared to 0.143 kmol H^+ kg^{-1} N for ammonium sulphate (Noble *et al*., 1997). The fertilizer-induced acidification process for both urea and ammonium sulphate is caused by the release of two hydrogen ions per unit of ammonium through the soil microbial process of nitrification and can be summarized in Equation 2.1 (Haynes and Hamilton, 1999):

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ \qquad (2.1)$$

The process of soil acidification associated with fertilization was confirmed by Graham *et al*. (1999) who measured mean pH values of 5.8 and 5.1 in unfertilized and fertilized treatments respectively, the difference being attributed to continual use of acidifying nitrogenous fertilizers for 49 consecutive years without concomitant liming.

The acidification rate was actually quite fast for South African soils since average pH values have been found to decline from 6.17 in 1980-82 to 5.61 in 1996-97, a 5.6-fold increase in acidification in terms of hydrogen ion activity over that period (Meyer *et al*., 1998). This rapid decline was confirmed by Qongqo and Van Antwerpen (2000) who estimated the rate of decline to be some 0.025 pH unit $year^{-1}$. Similarly, in Papua New Guinea, Hartemink (1998c) found that the pH value of topsoil declined from 6.5 in 1979 to around 5.7 in 1996, an average decline of about 0.047 pH unit $year^{-1}$ (Figure 2.7). The initial decrease from 1979 to 1982 was probably caused by the increased mineralization of organic matter associated with initial cultivation, while the decrease in the 1990's coincided with the application of ammonium sulphate instead of the previously used urea.

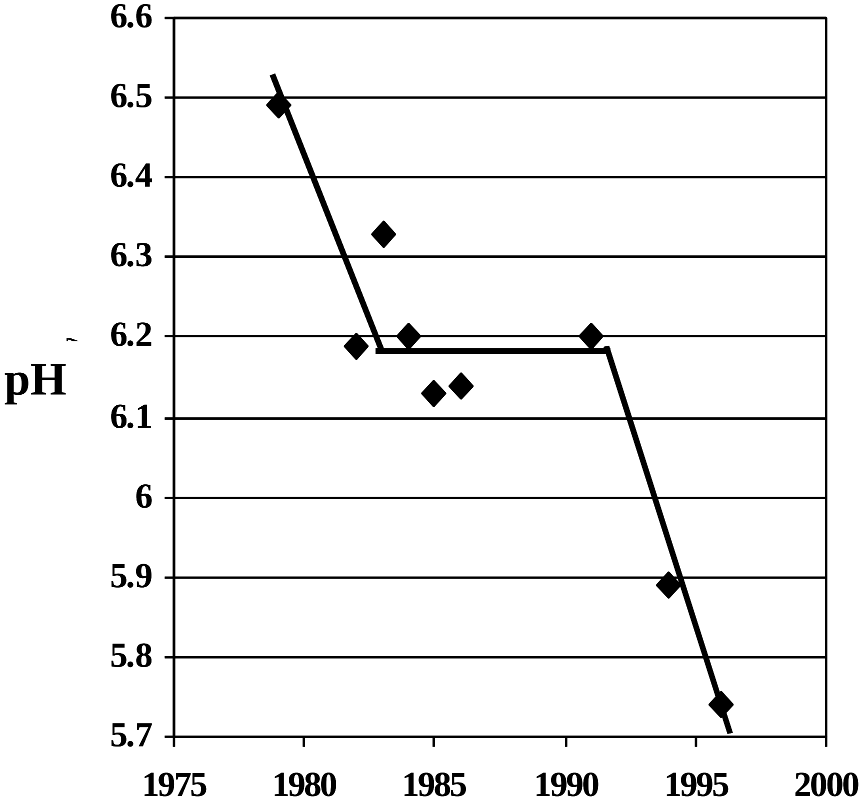


Figure 2.7 Decline of topsoil pH through time on account of sugar cane production in Papua New Guinea (adapted from Hartemink, 1998c).

In addition to topsoil acidification, a significant decrease of 0.2 to 0.4 pH units after 10 years of continuous sugar cane cultivation was also recorded in the subsoil (Figure 2.8). Hartemink (1998c) estimated that the soil under study had a buffering capacity of 125 kmol H^+ ha^{-1} pH^{-1} and warned that if the current fertilizer practices were maintained, it would take only ten more years for the mean soil pH to fall below the critical threshold of 5.0.

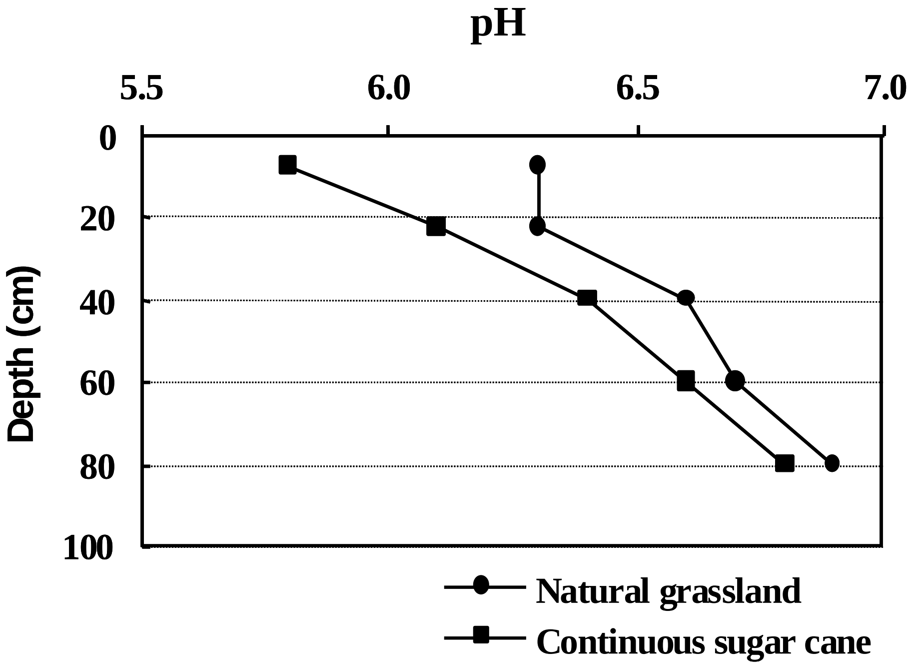


Figure 2.8 Change in subsoil pH after ten years of continuous sugar cane production in Papua New Guinea (compiled from Hartemink, 1998c).

There is little doubt that soil acidification occurs following the introduction of sugar cane on virgin soil, with long-term negative impact on soil quality. For instance, Noble *et al*. (1997) reviewed the linkage between sugar cane production and soil acidity and concluded that the continual decline in soil pH and associated infertility could have a significant impact on the long-term sustainability of sugar cane production systems. For their part, Schroeder *et al*. (1994) were concerned that acidification was becoming a major problem in South Africa, describing it as the most important yield-limiting factor in KwaZulu-Natal. Increased acidity with continuous cropping was identified as part of the chemical and physical degradation of soils in the South African sugar industry. This was confirmed by Meyer *et al*. (1998), who found a marked increase in soil acidification across the South African sugar industry. This decrease in soil pH associated with sugar cane cultivation can be considered to be a menace to the long-term fertility of the soil, and by extension, to the sustainability of the sugar industry if no corrective measures such as liming are taken.

2.3.3.2 Cation exchange capacity

The cation exchange capacity (CEC) was generally lower for soils under sugar cane compared to those under native vegetation (Wood, 1985; Henry and Ellis, 1996). Such an observation is not surprising since CEC is directly related to SOM content, and the latter has been demonstrated to generally decrease following sugar cane cultivation. Masilaca *et al*. (1986) differentiated between topsoil and subsoil CEC. While topsoil CEC tended to decline on account of lower OM content, the subsoil CEC increased. This was probably caused by the downward movement of OM when the soil was ripped and rotovated during the initial land preparation. On the other hand, Hartemink (1998b) found that the CEC decreased significantly with time throughout the soil profile (Figure 2.9). McLean (1975) was the exception in that he did not note any change in topsoil CEC.

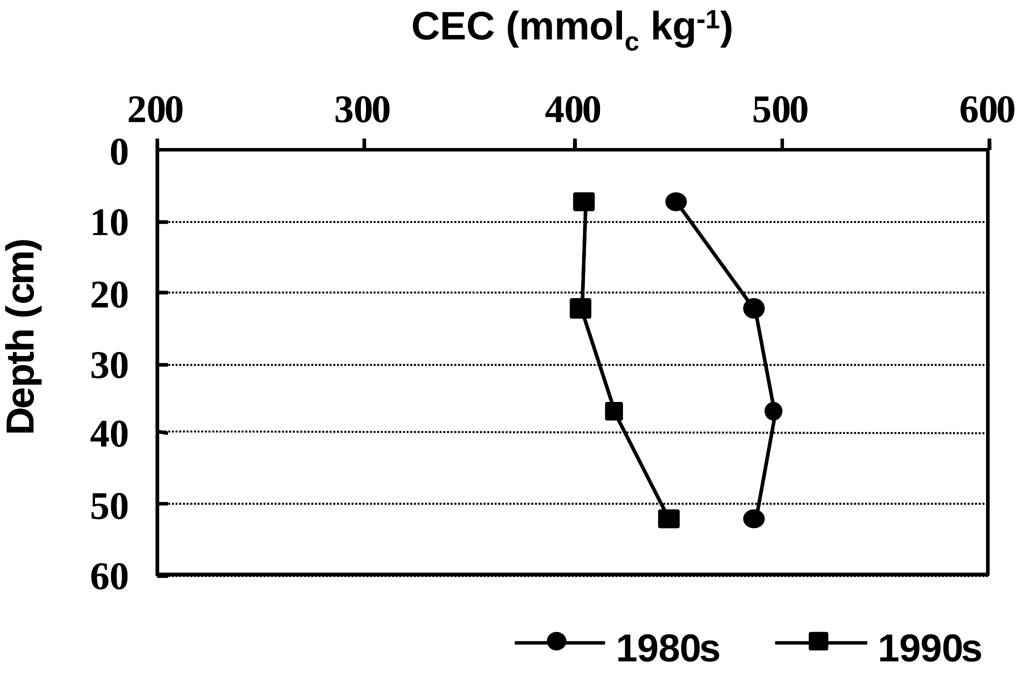


Figure 2.9 Change in the CEC of a soil profile after ten years of continuous sugar cane production in Papua New Guinea (compiled from Hartemink, 1998b).

2.3.3.3 Plant available nutrients

The levels of plant available nutrients in sugar cane soils might be higher or lower than in virgin ones, depending on whether fertilizer inputs were higher or lower than the amounts of nutrients removed in the harvested crop, plus any other losses such as leaching (Haynes and Hamilton, 1999). Two important exchangeable bases, namely calcium and magnesium, have been found to decrease in several studies (Wood, 1985; Masilaca *et al*., 1986; Van Antwerpen and Meyer, 1996; Meyer *et al*., 1998; Qongqo and Van Antwerpen, 2000). Wood (1965) has quantified the decrease in calcium, which fell from 922 mg kg^{-1} in virgin soil to 656 mg kg^{-1} in sugar cane soil. It appears that, in most cases, insufficient amounts of bases are being added to compensate for crop removal and leaching (Masilaca *et al*., 1986).

Similarly, exchangeable potassium levels tend to decrease, through both removal by cane and leaching losses. In Papua New Guinea, Hartemink (1998b) noted a decrease in potassium in newly planted soil from 14.2 to 8.5 $mmol_c$ kg^{-1}. Henry and Ellis (1996) also noted that levels of potassium have declined over the soil profile in Swaziland and that this deterioration was further aggravated by increasing imbalances between basic cations as shown by the increases in (Ca+Mg)/K ratios. By contrast, the opposite was noted in South Africa, with a build-up of potassium in soils under sugar cane, which could be directly attributed to an overuse of potassium fertilizers by growers (Meyer *et al*., 1998).

The levels of extractable phosphorus in sugar cane soils depend on fertilizer use and have been found to both increase (Wood, 1985; Henry and Ellis, 1996) and decrease (Van Antwerpen and Meyer, 1996; Meyer *et al*., 1998). McLean (1975) measured an increase in phosphorus from 14.2 mg kg^{-1} in a virgin soil to 30.5 mg kg^{-1} in sugar cane soil, while Hartemink (1998a) observed the opposite, having measured a decrease from 40 mg kg^{-1} to 28 mg kg^{-1} in a space of fifteen years. These changes were mostly confined to the topsoil and very little phosphorus was found to be removed from the soil horizons deeper than 30 cm.

2.3.3.4 Salinity and/or sodicity

Salinity and/or sodicity of soils are expressed in terms of changes in their electrical conductivity (EC) and sodium adsorption ratio (SAR). Changes in these parameters occurred in sugar cane soils essentially under irrigated conditions and were dependent on the quality of irrigation water. In Swaziland, it was found that sugar cane production had no negative effect on salinity or sodicity of a duplex soil (Henry and Ellis, 1996). However, the EC and SAR of this soil decreased dramatically, reflecting the effects of good surface and subsurface drainage, the use of irrigation water with low electrolyte concentration and the application of gypsum. The opposite situation was found in South Africa, where a higher EC and SAR were measured in irrigated sugar cane soils compared to virgin ones, with a build-up of salinity and sodicity in such areas (Van Antwerpen and Meyer, 1996).

2.3.4 Physical parameters

2.3.4.1 Bulk density

Bulk density was the main soil physical quality indicator to be affected when soils under sugar cane were compared to those under native vegetation. Thus, soils had an increased bulk density following the introduction of sugar cane into hitherto virgin area, clearly demonstrating that sugar cane production had a compacting effect on soil. This compaction was related to mechanized operations and therefore occurred mainly within the zones of machinery traffic. In the absence of traffic, the soil would probably not be compacted. For instance, Wong You Cheong and Chan (1977) did not observe any change in bulk density in their study on long-term cultivation, probably because of the limited use of heavy machinery in sugar cane production in Mauritius at that time.

However, heavy machinery has been increasingly utilized over the years for sugar cane production in many countries. As a result, it is not surprising to find a significant increase in bulk density of the topsoil under sugar cane compared to the virgin situation (e.g. McLean, 1975; Wood, 1985; Van Antwerpen and Meyer, 1996). Compaction was most marked in the inter-row, where most of the traffic occurs. This is confirmed by Hartemink (1998b), who found that the bulk density was significantly higher under the cane inter-row than under grassland, but there was little compaction under the cane row (Figure 2.10). The topsoil bulk density of the inter-row was higher by 0.20 g cm^{-3}, an average increase of 19% when compared to natural grassland. McGarry *et al.* (1996) also noted a similar increase in the topsoil bulk density, which was higher by 10 to 17%.

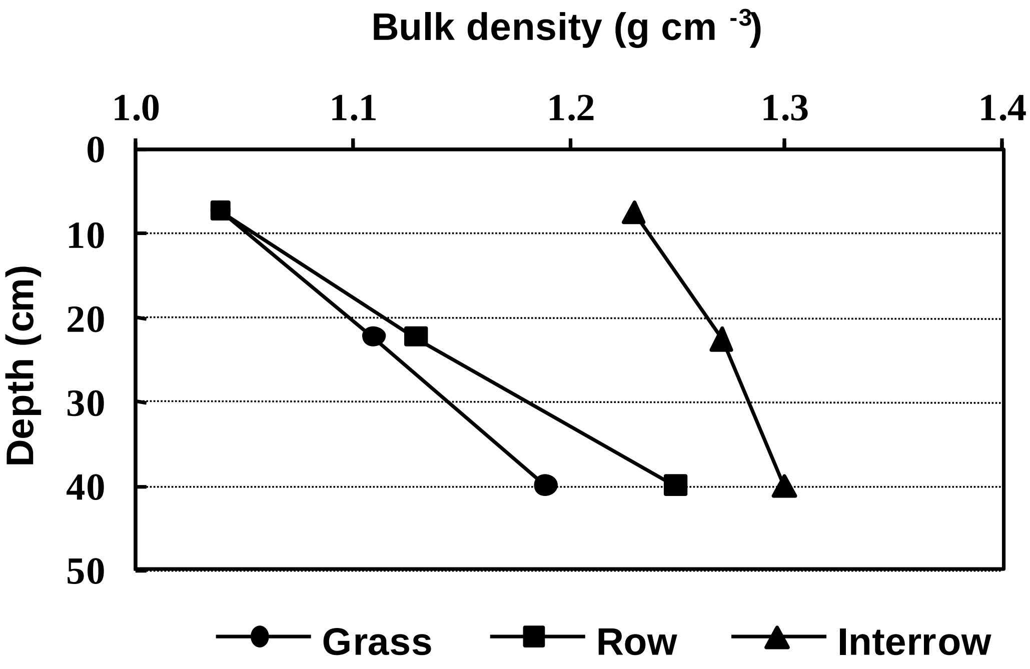


Figure 2.10 Bulk densities recorded beneath sugar cane inter-rows and rows and in grassland (adapted from Hartemink, 1998b).

Qongqo and Van Antwerpen (2000) were able to determine the average rate of compaction for two sites in South Africa. They found an increase in bulk density from 1.56 to 1.77 g cm^{-3} in 50 years at one site, giving a compaction rate of 0.004 g cm^{-3} per year. At the other site, the bulk density increased from 1.18 g cm^{-3} to 1.33 g cm^{-3} in 30 years, equivalent to a compaction rate of 0.005 g cm^{-3} per year. For their part, McGarry and Bristow (2001) found bulk density increases of 18% and 22% in sugar cane inter-rows and rows respectively compared to rainforest at one site, and further increases ranging between 3% and 13% at other sites.

Traffic on account of mechanization is associated with several cultural operations. Relative contributions to compaction from each source are probably of different magnitudes. McLean (1975) differentiated between two main sources of compaction, namely short-term compaction associated with mechanical harvester and bin traffic, and long-term compaction associated with cultivation during crop growth. Wood (1985) suggested that compaction and breakdown in soil structure were due to soil damage caused by harvester and haulout traffic, excessive cultivation, and situations where farmers had been forced to harvest under excessively wet conditions. Ng Cheong *et al*. (1999) found that soil compaction did occur with harvester traffic, even under relatively dry conditions, but without significantly affecting cane yield. For their part, Henry and Ellis (1996) ruled out trafficking as the sole responsible factor for increased bulk density because compaction was also observed at depth, but failed to identify other potential sources of compaction.

2.3.4.2 Infiltration rate

Compaction, surface crusting and other forms of physical deterioration will affect the infiltration rate of water into the soil. A reduction in stabilized infiltration rate is thus a clear sign of deterioration in soil physical properties. In most cases, soils under sugar cane had a lower stabilized infiltration rate than those under native vegetation. For instance, Garside *et al*. (1997) found that infiltration rates were lower in cropped fields compared to virgin ones, the lower rates being generally associated with increases in soil strength. Their conclusion was that compaction was directly affecting infiltration rate and that effective rooting depths could also be potentially affected. Hartemink (1998b) found, as illustrated in Figure 2.11, that the average infiltration rate (after more than 4 hours) in the sugar cane inter-rows was very low (average 16 mm h^{-1}) compared to grassland (average 259 mm h^{-1}) or sugar cane rows (average 290 mm h^{-1}).

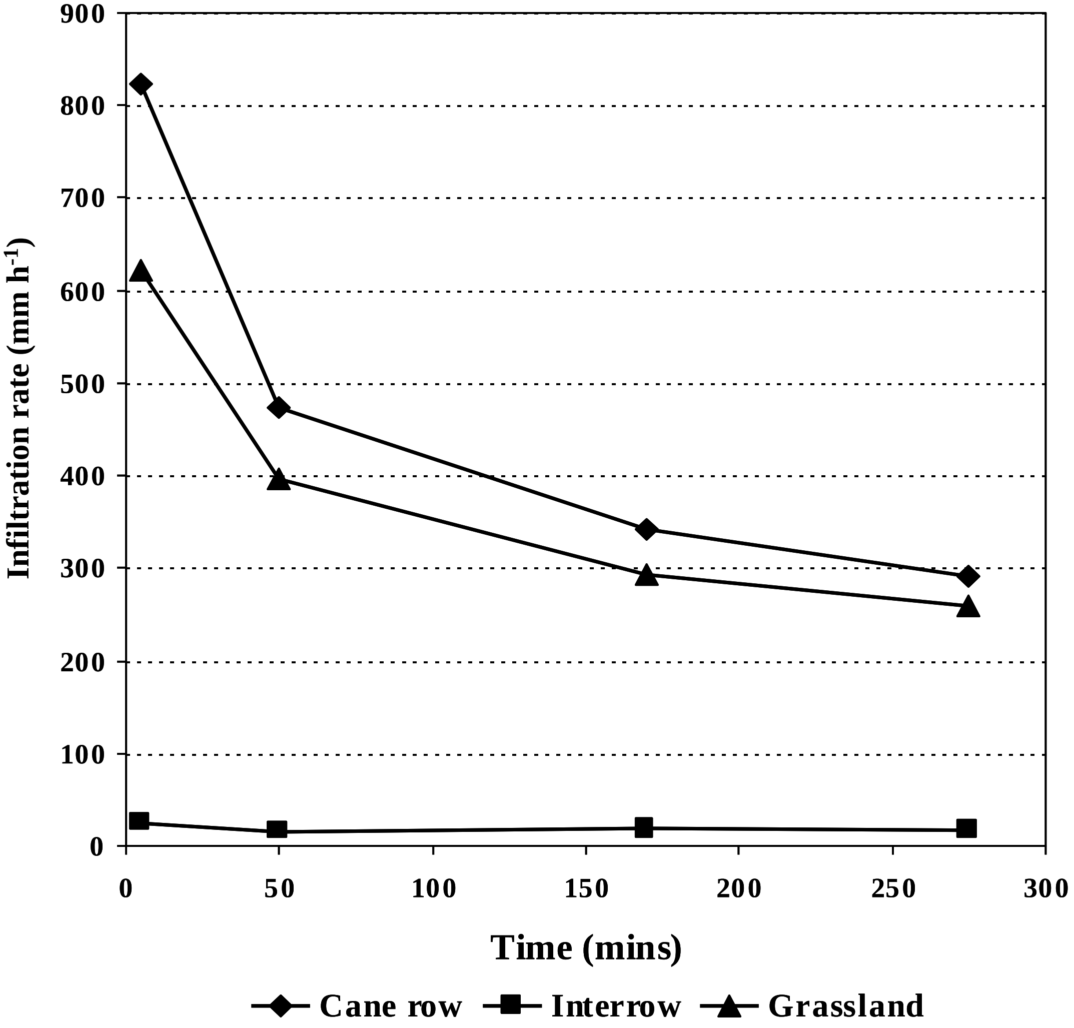


Figure 2.11 Infiltration rates recorded in sugar cane inter-rows and rows and in grassland (compiled from Hartemink, 1998b).

There was no significant difference between the infiltration rates of the grassland or sugar cane rows, suggesting that it was not the presence of sugar cane *per se* that affected infiltration rate, but more likely the traffic associated with the crop. This is partly confirmed by Henry and Ellis (1996), who found that cropping had little effect on the final infiltration rate of a duplex soil while that of an Oxisol deteriorated under cropping from 16.2 to 8.7 mm h^{-1}.

2.3.4.3 Plant available water

There is little consistency in the way in which plant available water (PAW) of a soil has been affected by the introduction of a sugar cane crop. In Mauritius, Wong You Cheong and Chan (1977) found that the effect of sugar cane cultivation on the PAW varied with soils and cropping conditions. Soils under sugar cane had lower PAW than soils under native vegetation in dry areas, but higher PAW in the wet zones. For their part, Masilaca *et al*. (1986) found no significant change in PAW at two sites and an increased PAW at a third site, but had no explanation to offer for these differences. Henry and Ellis (1996) also found little effect of cropping on PAW, with a lower capacity of 2.8% for soils under sugar cane. In South Africa, Van Antwerpen and Meyer (1996) noted a significant increase in PAW with cultivation in a dryland situation. Conversely, Garside *et al*. (1997) found lower PAW in cane soils in Australia, which were also generally associated with increases in soil strength. In the same country, McGarry and Bristow (2001) measured a reduction in PAW at four sites, which ranged from 8% to 20%.

2.3.4.4 Aggregate stability

In general, soils under sugar cane had much lower aggregate stability than those under native vegetation (Wong You Cheong and Chan, 1977; McGarry *et al*., 1996). The effect tended to be more marked in aggregates at the soil surface. McGarry *et al*. (1996) noted that aggregates from the top 10 cm of a cultivated site slaked after 2 hours, while aggregates from an uncultivated site did not slake at all. Qongqo and Van Antwerpen (2000) found that soil aggregate stability decreased as the period under sugar cane increased, with a rate of 0.87% per year for a sandy loam and 0.64% per year for a clayey soil. Dominy *et al*. (2001) explained this decreased aggregate stability by the fact that, with increasing years under sugar cane, SOM level declined and soil aggregates became less strongly bound, thereby reducing the aggregate stability.

2.3.4.5 Particle size distribution

The evidence suggests that there is very little difference in textural properties between sugar cane-planted soils and those under native vegetation (McLean, 1975; Van Antwerpen and Meyer, 1996). McGarry and Bristow (2001) studied the soil's textural properties at seven sites and found that only one displayed differing textures. Wong You Cheong and Chan (1977) found some changes in clay content, but these varied with soil and no reason could be assigned to the measured differences (Table 2.2). However, it is interesting to note that under sub-humid conditions, sugar cane cropping appeared to have led to an increase in clay content at the expense of the silt content, possibly as a result of topsoil mixing with the more clayey subsoil. On the other hand, there was a decrease in clay content in one soil from the super-humid region, and this could be due to soil erosion, with the clay fraction being more susceptible to detachment and entrainment by rainfall.

Table 2.2. Changes in particle size fractions to 45 cm depth in Mauritius soils associated with sugar cane cropping (Wong You Cheong and Chan, 1977).

Soil*	**Climate**	**Soil under native vegetation**			**Soil under sugar cane**		
		Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Clay (%)
P	Sub-humid	31.8	34.6	33.6	31.2	21.4	47.4
L	Sub-humid	11.8	25.8	62.5	6.5	19.6	73.8
B	Super-humid	36.1	27.6	36.3	50.7	22.0	27.3
F	Super-humid	47.9	25.8	26.3	46.3	27.9	25.8

* P: Latosolic Reddish Prairie L: Low Humic Latosol

B: Latosolic Brown Forest F: Humic Ferruginous Latosol

2.4 Conclusion

The quality of a soil determines its capacity to perform several functions, namely sustaining plant and animal productivity, maintaining or enhancing water and air quality, and supporting animal health and habitation. Since it is not possible to measure how the soil is performing these various functions, soil quality is determined through indicators that are used in the screening of soil condition. Research work on soil quality in South Africa, Australia and elsewhere has led to the identification of possible indicators of soil quality for soils under sugar cane. These indicators are biological – soil organic matter and soil microbial biomass; chemical – pH, cation exchange capacity and exchangeable bases; and physical - soil texture (particle size distribution), soil structure (aggregate distribution and stability), bulk density, plant available water and stabilized infiltration rate.

These quality indicators have been determined for soils under sugar cane and compared to those of soils under native vegetation in countries such as South Africa, Australia, or Papua New Guinea. Such comparisons have clearly indicated that sugar cane soils are degraded in these countries and that, under current conditions, the long-term sustainability of sugar cane production is not guaranteed. Several cultural practices have been held responsible for this degradation, particularly tillage, fertilization, mechanization and irrigation. There is no reason why Mauritius should be an exception to the rule, since the cultural practices associated with sugar cane cultivation in Mauritius are similar to those of the aforementioned countries. It is therefore essential to determine the extent to which the quality of soils in Mauritius is affected by sugar cane cultivation, before any remedial action can be taken to ensure the long-term sustainability of the industry.

CHAPTER 3

CHARACTERIZATION OF THE STUDY AREA

3.1 Introduction

In this chapter, a general description of the island of Mauritius will be presented, with particular reference to its physical environment and its sugar industry. Its geography and physiography will be briefly described. Details will be given about the climate of the island, with emphasis on variations in temperature and rainfall, which give rise to different agro-climatic zones. This will be followed by an account of the geology of the island, which plays an essential role in the nature of its soils. The latter will be described using the soil maps of 1962 and 1984. Finally, the current status of the sugar industry of Mauritius will be reviewed with emphasis on its contribution to the economy of the island.

3.2 Location

Mauritius is an island of volcanic origin situated between the parallels of $19^o58'$ and $20^o32'$ south latitude and the meridians of $57^o17'$ and $57^o46'$ east longitude in the South West Indian Ocean (Figure 3.1). It is approximately 800 km east of Madagascar and 2000 km off the coast of continental Africa. The island has an elliptical shape, with a major axis running North North East – South South West over a distance of 61 km and perpendicular to this is a minor axis of 46 km. The total land area is in the order of 1860 km^2.

3.3 Physiography

Mauritius consists essentially of a ring of peaks about 600 to 900 m high, enclosing a central plateau rising from about 300 m in the north to 600 m in the south west. To the north of the mountains, the northern plain with the prominent volcanic cones of Mont Piton, The Mount, Butte Aux Papayes and Forbach falls gently to the sea with an average slope of less than 1%.

To the west, a coastal plain about 5 km wide in the north tapers down to the Morne Babant peak in the south coast of the island. In the west and south, the lavas of the volcanic cones which built up the central plateau have spilled around the mountain ranges and flowed to the sea forming coastal plains with a general slope of about 2%. In the south west corner of Mauritius, the area of Chamarel, derived from ash produced at the time of the Early Lavas of the Younger Volcanic Series, has been strongly dissected and eroded, as have the southern slopes of Savanne and Grand Port mountain ranges. The island is drained by several river systems distributed mainly in the Intermediate Lavas; the rivers themselves though not large, are very deeply incised (Parish and Feillafé, 1965)**.**

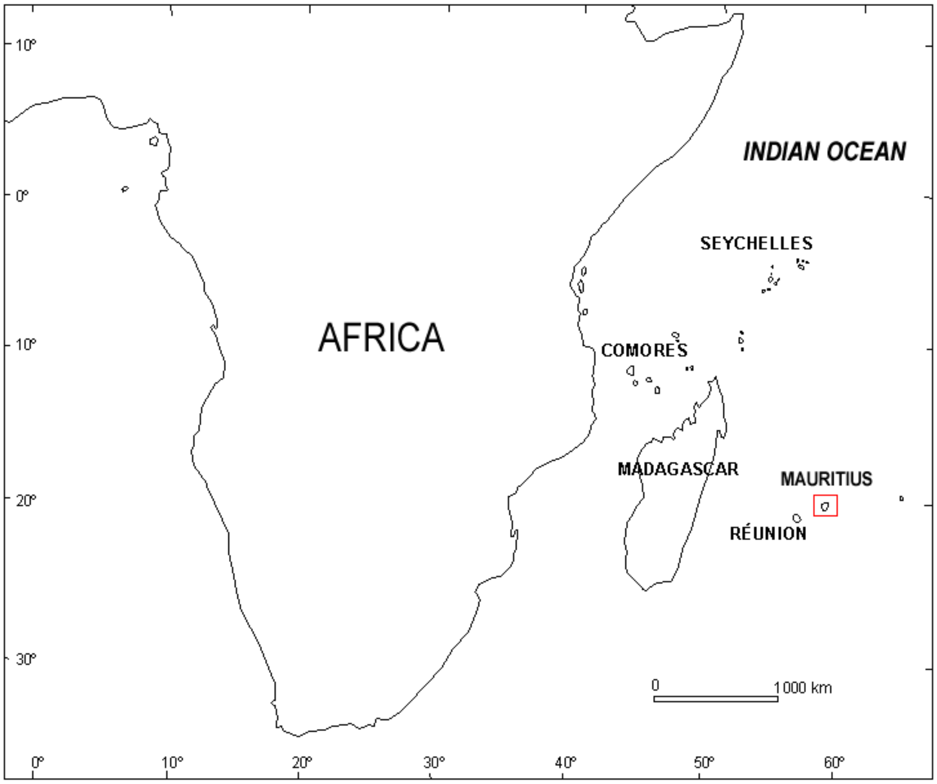


Figure 3.1 Location of Mauritius in the South West Indian Ocean (adapted from Université Michel de Montaigne – Bordeaux 3, 1997)

Thus, there are three distinct topographic patterns connected with the age of the parent lava. There are the comparatively small but often scenically dramatic mountain ranges of the oldest lavas. Then, there are the gently rolling topography of the Intermediate Lavas of the Younger Volcanic Series with deeply incised rivers and some terraces and now stabilized gullies. Finally, there are the Late Lavas, with many extremely rocky areas of distinctly hummocky appearance and an almost complete absence of surface drainage, dominated by the vents that gave rise to them (Parish and Feillafé, 1965).

3.4 Climate

3.4.1 Temperature

Mauritius is a small isolated land mass situated near the southern edge of the tropical belt. It is practically free from continental influences and thus enjoys a maritime climate, viz. tropical-maritime during summer (November to April) and sub-tropical in winter (May to October). However, the weather does not remain the same for more than a few days consecutively as it is affected by disturbances of both temperate and tropical types (Padya, 1984). The South-East trade winds are dominant in the winter months, giving way to periods of calm and light winds in summer which are frequently interrupted by tropical depressions or cyclones. Very high winds and intense rainfall characterize these tropical depressions.

The highest mean temperature occurs in February and the lowest in August while the range of the mean temperature is about 5.5 ^{o}C at most places. However, the mean daily range of temperature is about 6 ^{o}C in the centre, and about 7 to 8 ^{o}C on the coast. The weather is also highly dependent on the island’s topography. Thus, midsummer temperatures at the centre are similar to midwinter temperatures on the coast (Padya, 1984).

3.4.2 Rainfall

The mean annual rainfall over the island as a whole is in the order of 2100 mm (Padya, 1984). Orography and prevailing winds have a distinct effect on rainfall distribution. Annual rainfall on the windward Eastern coast is around 1600 mm, rises to almost 4000 mm near the centre and then decreases gradually to less than 1000 mm on the leeward Western coast (Figure 3.2).

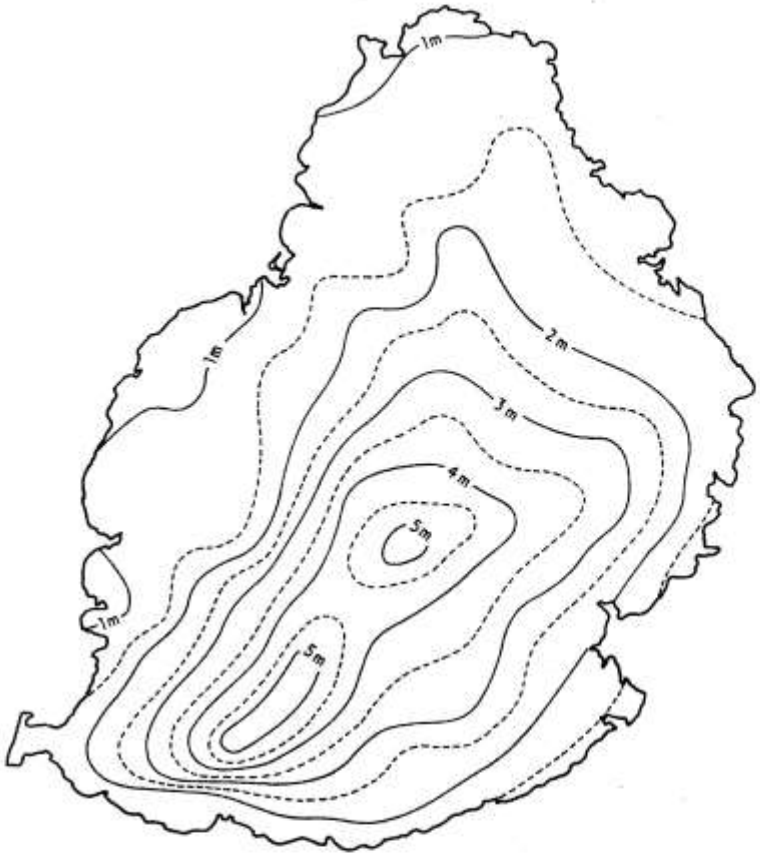


Figure 3.2 Mean annual rainfall distribution over Mauritius (Parish and Feillafé, 1965)

About 70% of the total rainfall occurs in the summer months of November to April. October is the driest month, with only 3.5% of the total, while March is the wettest with 15% of the total. The monthly average increases from November through March, decreases sharply in April and May, and then decreases more gradually until October.

Thermal and moisture efficiency indices have been derived from rainfall and air temperature data. Mauritius has been divided into distinct agro-climatic zones according to Thornthwaite's classification using these indices (Halais and Davy, 1969). These agro-climatic zones range from super-humid mesothermal in the centre to semi-arid megathermal on the western coast. The semi-arid zone covers only a very small area (0.3% of the island), and is therefore of no significance. Hence the island is divided into three main agro-climatic zones, namely sub-humid, humid and super-humid. The sub-humid zone covers the low rainfall (< 1600 mm annually), high temperature region confined to the coastal belt which is more important on the leeward side; it covers 19.4% of the island. The humid zone is an intermediate rainfall region (1600 – 2600 mm annually) between the coastal belt and the centre of the island, representing 34.7% of the island. Finally, the super-humid zone is a high rainfall (> 2600 mm annually) and relatively low temperature region, in the higher parts of the island's centre and covers 45.6% of the island.

3.5 Geology

The rocks of Mauritius, apart from some consolidated coral and shell debris and the reefs and dunes around most of the coast, are entirely volcanic in origin and are of two distinct geological ages. The older volcanic series, as defined by Simpson (1951), gave rise to the highly eroded mountainous features of the landscape. The foothills and bases of these mountains were then flooded by younger lavas which formed the central plateau and the plain of the north. An intermediate stage of volcanic activity which was confined to the south-west corner of the island gave rise to a series of lava flows and a considerable area of ash deposition quite distinct from both the older and recent lavas.

The Older Lavas have thus given rise to the Older Volcanic Series in or before the Early Tertiary (Simpson, 1951). This was followed by a major erosion interval before the advent of the Younger Volcanic series which gave rise to the Early Lavas in the Late Tertiary. There followed a minor erosion interval sequence before the same Younger Volcanic Series gave rise to the Late Lavas in the Pleistocene.

The Older Volcanic Series consist mainly of compact and unvesiculated olivine basalt and coarse agglomerate, cut by numerous dykes and a few intrusive trachyte domes. The Early

Lavas of the Younger Series, which are mildly vesiculated olivine basalts, built up the south-western plateau of Plaine Champagne and Pétrin, whilst the highly dissected Chamarel area was formed by the pyroclastic activity preceding the pouring out of the very liquid lavas. The Late Lavas of the Younger Series followed after a short erosion interval, without a preceding phase of pyroclastic activity. Flow after flow of lava poured out from a series of shield volcanoes flooding almost the whole island, and building up to a height of 660 m near the central town of Curepipe (Figure 3.3).

Twenty-five vents on well-preserved shield volcanoes exist, all lying on a line trending NNE - SSW from end to end of the island; some of the northern vents are surrounded by a carpet of pyroclasts ejected during the last stage of their activity.

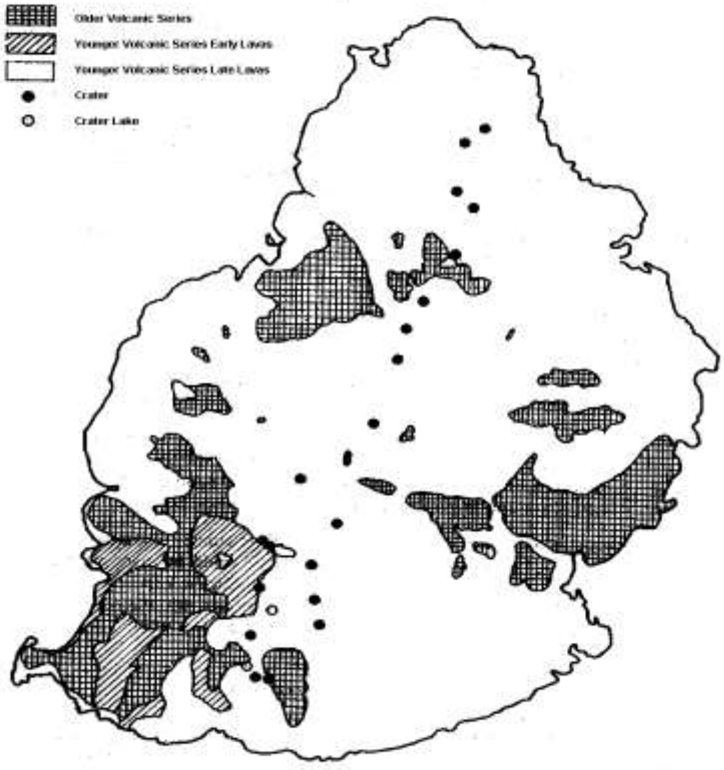


Figure 3.3. Simplified geological map of Mauritius (after Simpson, 1951)

For the purpose of soil classification, Parish and Feillafé (1965) have further sub-divided the Late Lavas of the Younger Volcanic Series, as the soils of the island fall into two distinct age categories, namely deep mature soils and shallow rocky soils. In many areas, relatively shallow layers of lava on which soils with varying degrees of maturity have developed overlie the deep mature soils. Parish and Feillafé (1965) have thus further divided the geology of Mauritius into Older Volcanic Series followed by Younger Volcanic Series comprising of Early, Intermediate and Late Lavas in chronological order. The Older Volcanic Series consist of mountain peaks and ranges, while the Early Lavas are associated with the south-western plateau of Pétrin and Plaine Champagne, and the highly dissected area of Chamarel. The Intermediate Lavas have given rise to deep soils with well developed drainage systems while the Late Lavas gave rise to rocky soils without surface drainage systems.

The country covered by the mature soils varies from a flat to a rolling topography, with deeply incised river gorges and some minor terraces, whilst the topography of the areas covered by the rocky soils tends to be hummocky and is almost completely free of any surface drainage system. The rocks and boulders of the mature soils are usually coarse grained doleritic basalts with some vesiculation, whilst the rocky soils contain doleritic basalts that are highly vesiculated. Apart from the Plaine des Roches up to the flanks of L'Escalier, which is of the pahoehoe lava type, the most recent lava flows of Mauritius give the appearance of having been of the aa type (Parish and Feillafé, 1965).

There are alternate layers of lava and soil in the sides of the deeply incised river gorges and at the exposed faces of the mountain ranges. In fact, the whole geology of Mauritius is made up of layers from different lava flows and weathered material on which have been superimposed the effects of erosion due to the torrential rains which occur during the cyclone season. Around the coast, raised coral reefs and consolidated shell and coral debris can be found overlying a deep tuff at heights of more than 20 m above sea-level. These observed features may be assigned to the fluctuations of the sea level during the Pleistocene glacial and inter-glacial periods and/or vertical movements of the land mass due to volcanic instability.

3.6 Soils

3.6.1 Soil Map of 1962

The first soil map of Mauritius with a scale of 1:100 000 (Figure 3.4) was published in 1962 (Parish and Feillafé, 1965) and this system is still the most commonly used within the cane-planting community. Owing to the close similarity between parts of the Hawaiian Islands and Mauritius with respect to geology, climate, soils and cropping, the classification system used by Cline in 1955 for the soil survey of the territory of Hawaii was applied to Mauritius. However, there are some noteworthy differences between the two islands, the main one being that, contrary to Hawaii, a large proportion of Mauritius is covered by rocky soils formed on the recent lava flows. The system was thus adapted to take into account such differences.

In this classification system, the soils are divided into zonal, intrazonal and azonal orders (Table 3.1). As with the Hawaiian system, the Great Soil Groups have been sub-divided into families, each of which represents an area of fairly uniform climate and topography, and therefore of similar soils.

Table 3.1. Soil Groups of Mauritius (Parish and Feillafé, 1965)

Zonal	Intrazonal	Azonal
Low Humic Latosol	Latosolic Reddish Prairie	Alluvial Soil
Humic Latosol	Latosolic Brown Forest	Regosol
Humic Ferruginous Latosol	Grey Hydromorphic	Lithosol
	Dark Magnesium Clay	
	Low Humic Gley	
	Ground Water Laterite	
	Mountain Slope Complex	

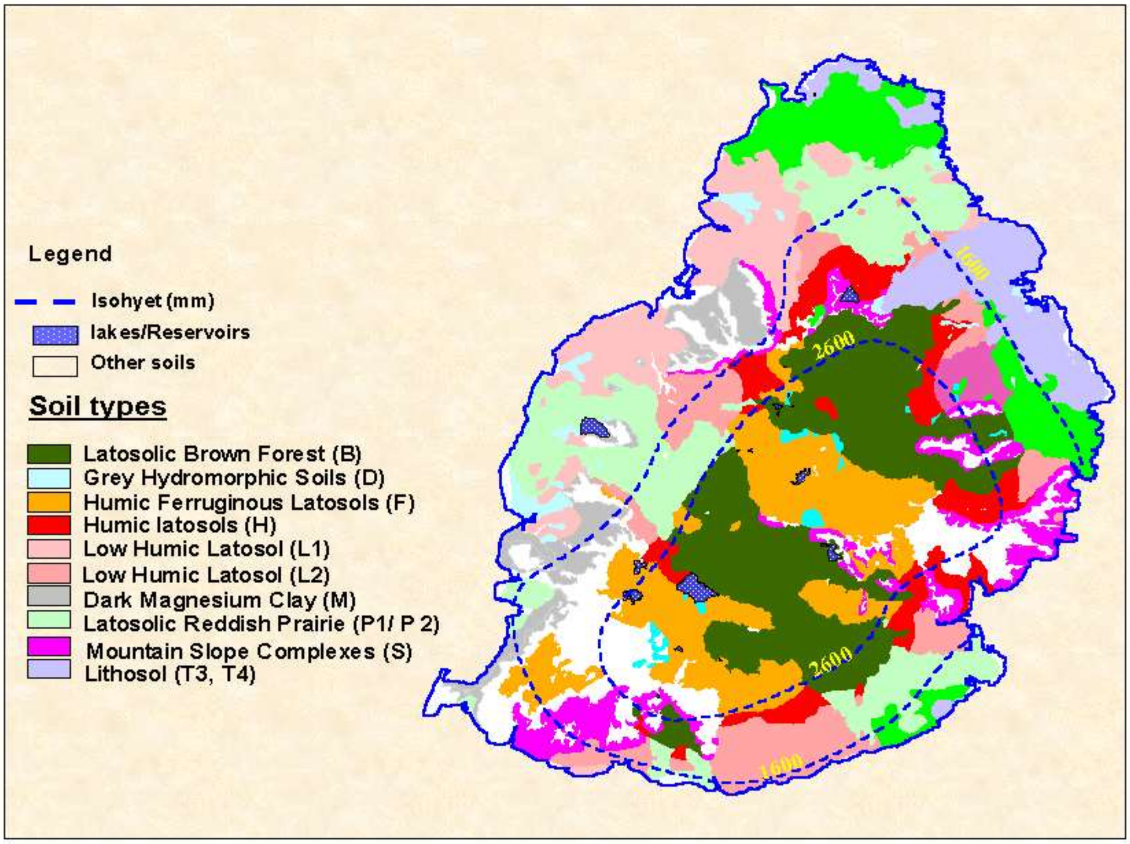


Figure 3.4 Soil map of Mauritius (after Parish and Feillafé, 1965)

3.6.1.1 Zonal soils

The zonal soils of Mauritius fall into the Latosol sub-order and are represented by three Great Soil Groups, the Low Humic Latosols, the Humic Latosols and the Humic Ferruginous Latosols. They have developed mainly on the Intermediate Lavas under a mean annual rainfall ranging from < 1000 mm to > 5000 mm. Surface and internal drainage are adequate and they have thus permitted the fullest expression of climate and vegetation as soil forming factors. Some chemical properties of the zonal soils are summarized in Table 3.2.

Table 3.2. Some chemical properties of the zonal soils (adapted from Parish and Feillafé, 1965)

Property	Soil group		
	L	H	F
pH	~6 - 7	5.4 - 6.2	5.5
CEC (meq%)	25	15 - 25	20
Organic matter (%)	4.8	5 - 7	6.9 - 10.4
Nitrogen (%)	0.27	0.26	0.3
C/N ratio	10.7	9.5 - 13.5	18

The Low Humic Latosols (L) have developed on the Intermediate Lavas within the sub-humid and low rainfall humid zones. They are deep to moderately deep soils with good internal drainage and a fairly high base status, with a low organic matter content. They have a red to brown A horizon that displays a strong medium to fine sub-angular blocky structure. Their B horizon is red to reddish brown, with a massive to weakly prismatic structure. The texture of the Low Humic Latosols is silty clay to silty clay loam. Kaolinite is the dominant mineral with goethite and sometimes gibbsite in lesser amounts. This soil group covers 16.4% of the total area of Mauritius and is divided into four families, namely Richelieu (L1), Réduit (L2), Ebène (L3) and Bonne Mère (L4).

The Humic Latosols (H) have developed on the Intermediate Lavas in the humid to super-humid zones, i.e. from a mean annual rainfall of 1500 to 3750 mm. They have a well-developed dark brown A horizon overlying a reddish brown B horizon which grades into parent material. Their texture is clay by mechanical analysis but they behave like silty clays. They contain equal quantities of kaolinite, goethite and gibbsite. This soil group covers 5.2% of the total area of Mauritius and is divided into two families, Rosalie (H1) and Riche Bois (H2).

The Humic Ferruginous Latosols (F) have developed on the Early and Intermediate Lavas of the Younger Volcanic Series and on the lavas of the Older Volcanic Series. They are strongly weathered soils occurring in the high rainfall region of the island with mean annual rainfalls ranging from 2500 to more than 5000 mm. They have a thin A1 horizon rich in organic matter, a crumb-structured A2 horizon with iron and aluminium oxide concretions overlying a compact B horizon which grades into parent material. The clay fraction is mainly gibbsite and goethite, with very little kaolinite. This soil group covers 11.4% of the total area of Mauritius and is divided into four families, namely Belle Rive (F1), Sans Souci (F2), Midlands (F3) and Chamarel (F4).

3.6.1.2 Intrazonal soils

The soils classified under this order are those that have developed under conditions where the effects of climate and vegetation are masked by local factors of environment such as relief, drainage and composition of the parent material. Soils developed on Late Lavas in the dry areas have been classified as Latosolic Reddish Prairie (P) soils and in the wet areas as Latosolic Brown Forest (B) soils. Soils in the dry valleys of the Older Volcanic series are the Dark Magnesium Clays (M). The Grey Hydromorphic (D) soils occur when drainage is poor on the Intermediate Lavas in dry areas, whilst the Low Humic Gley (G) occurs in the humid and super-humid zones. The Ground Water Laterites occur only in the super-humid zone. The Mountain Slope Complexes (S) are characterized by strong erosion. Some chemical properties of the intrazonal soils are summarized in Table 3.3.

The Latosolic Reddish Prairie soils have developed on the Late Lavas, with annual rainfall lower than 2500 mm. They have a dark coloured A horizon, high in organic matter, which grades into a lighter, reddish or reddish-brown B horizon. The profile contains varying amounts of cobbles and gravel of unweathered or slightly weathered basalt and bed-rock exposures are common. They vary in texture from clay loams to silty clays. The clay fraction is dominantly kaolinite, with less than 5% iron and aluminium oxides and no montmorillonite. This soil group covers 19.9% of the total area of Mauritius and is divided into three families, namely Médine (P1), Labourdonnais (P2) and Mont Choisy (P3).

Table 3.3. Some chemical properties of the intrazonal soils (adapted from Parish and Feillafé, 1965)

Property	Soil type					
	P	B	M	D	G	S
pH	6.0 - 7.1	5.0 - 6.3	6.9	7	4.3 – 5.5	5.2 – 6.7
CEC (meq%)	30 - 50	30	>50	35	10	29 - 37
Organic matter (%)	6.8	12	>7	4.9	10	5.3 – 6.2
Nitrogen (%)	0.3	0.6	0.30	0.28	N/A	N/A
C/N ratio	11	14	15	10	N/A	N/A

N/A: Not Available

The Latosolic Brown Forest soils have developed on the Late Lavas in the super-humid area. In time, they should develop into Humic Ferruginous Latosols and in fact, there are some areas where there has been so much iron oxide deposition that they are very close to being zonal soils. They are characterized by a dark coloured A horizon, very high in organic matter, that grades into a lighter, coloured B horizon over parent rock at shallow depth. The profile contains varying amounts of weathered cobbles and gravels. They vary in texture from clay loams to silty clays or clay. The clay fraction has moderate to very small amounts of kaolinite, and rather more gibbsite than goethite. Many small waterlogged spots are encountered within this soil group, which covers 16.5% of the total area of Mauritius and is divided into two families, namely Rose Belle (B1) and Bois Chéri (B2).

The Dark Magnesium Clays have physical properties showing the dominant influence of montmorillonite with a high degree of saturation by magnesium. These soils have developed under low rainfall conditions, 1000 to 1500 mm annually, on the lower slopes of the mountains and in valleys where the parent rock is of the Older Volcanic Series. They are self-mulching black or dark grey clays with accumulations of calcium carbonate in the lower horizons. As they are formed from colluvium and alluvium, there are often gravels and cobbles in the profile and they tend to be transitional to Lithosols on the steeper slopes of mountains. Dark Magnesium Clays are heavy clay soils, with montmorillonite completely dominant and very little kaolinite. There are two families in this soil group, Plaine Lauzun (M1) and Magenta (M2), covering 3.8% of the total area of Mauritius.

The Grey Hydromorphic soils are plastic clays formed as a result of periodical water logging. They occur mainly in the sub-humid zone (1250 mm per annum) on Intermediate Lavas. They are characterized by an A horizon with a greyish cast over a B horizon with grey, yellow and brown mottlings. There are two families in this soil group, Balaclava (D1) and Saint André (D2) covering 1.1% of the total area of Mauritius.

The Low Humic Gley is characterized by an almost permanently high water-table which has created a zone of strongly reducing conditions. The group is divided into two families, Pétrin (G1) and Valetta (G2). In the Pétrin family, a shallow A horizon tinted with some organic matter overlies an ash grey horizon. The Valetta family displays a more or less humic A horizon, over a horizon with prevalent mottlings and small iron concretions, over the gley horizon proper.

The Ground Water Laterites occur only in the super-humid zone on the Early Lavas of the Younger Volcanic Series. They are completely senile soils with a permanently high water-table.

The Mountain Slope Complexes are mapped between the boundary of the Intermediate and Late Lavas of the Younger Volcanic Series and the Older Volcanic Series and the 30% slope contour. They occur between 1500 and 5000 mm rainfall and the parent material are the lavas of the Older Volcanic Series and the Early Lavas of the Younger Volcanic Series. Two families have been defined, which cover 5.3% of the total area of Mauritius, the Nicolière family (S1) for the sub-humid to humid region and the Ferney family (S2) for the super-humid region. The Nicolière family is a shallow greyish brown clay soil with unweathered rock in the profile.

3.6.1.3 Azonal soils

Soils classified as azonal have little or no profile development, apart from some organic matter accumulation in the surface horizon. They are thus likely to show some of the characteristics of the zonal soils occurring in the same area. Three main soil groups have been classified, the Alluvial soils, the Regosols and Lithosols.

The Alluvial soils are young soils developed from recent alluvium. They may differ on the basis of texture according to the nature of the alluvium. Thus, some are silts or silty clays, with or without pebbles, whilst others are clays washed from the neighbouring mountainsides.

The Regosols consist of soils with little or no profile development on deep unconsolidated deposits other than alluvium. The parent material is wind-blown coral sand. The A horizon is a dark brown sand or loamy sand formed by a mixture of coral sand and organic matter over a light grey or very pale brown coral sand. Their pH averages 8.5.

The Lithosols are situated on the rough broken land of mountains and gorges, and rock-land comprising areas of almost unweathered rock. Four land types have been separated, two of which are rough broken land (T1 and T2) and the other two are rock-land (T3 and T4). The T1 occurs on mountains or very steep slopes where soil development is offset by erosion. On the other hand, the T2 occurs in the mountain gorges. The T1 and T2 land types occur on slopes exceeding 30% and vary considerably in their properties depending on rainfall, slope stability and ground cover. The T3 is a skeletal soil high in organic matter on hummocky bed-rock while T4 has a thin cover of soil high in organic matter on smooth bed-rock lava. The

T3 and T4 land types are rich in organic matter and are slightly to moderately acid with a CEC of around 65 meq 100 g^{-1}. This soil group covers 16.6% of the total area of Mauritius.

The Great Soil Groups of Mauritius can be correlated with the US and FAO soil classification systems, namely Soil Taxonomy (Soil Survey Staff, 1999) and World Reference Base for Soil Resources (FAO, 1998). In general, the Latosol is equivalent to the Oxisol (Soil Survey Staff, 1999) and to either the Nitosol or Acrisol (FAO, 1998). On the other hand, the Latosolic soil is equivalent to the Inceptisol (Soil Survey Staff, 1999) and to the Cambisol (FAO, 1998).

3.6.2 Soil map of 1984

Willaime (1984) has produced a more recent soil map with a scale of 1:50 000, the *Carte Pédologique de l'Ile Maurice*. This map is based on the French CPCS system. Willaime states that the interaction of essential pedogenetic factors like parent rock, topography and climate has given rise to soils under the influence of two major processes:

- In areas that are sufficiently humid and well-drained, the process of "ferrallitisation", characterized by the eluviation of bases and silica, the release of iron and aluminium oxides and hydroxydes, and the formation of clays of the kaolinite family
- In relatively dry, poorly-drained areas, the process of "bisiallitisation", characterized by the removal of bases and silica, and the genesis of expanding clays of the montmorillonite family.

Two secondary processes can further superimpose their effects on the two major processes above:

- Erosion, giving rise to eroded soils through sediment loss or to soils formed under the re-deposition of eroded material
- Hydromorphism, which influences soils in areas with poor external drainage.

Four broad soil categories have been defined in this system:

1. Poorly evolved soils, such as those found on mountains, in gorges, etc.
2. Soils mainly affected by the “bisiallitisation” process, namely vertisols and other dark soils
3. Soils mainly affected by the “ferrallitisation” process, namely “ferrallithic” soils
4. Soils mainly affected by water-logging phenomena, namely hydromorphic soils.

This system is further refined for the most important soil category, the “ferrallithic” soils, which cover more than 75% of the island. In this case, the intensity of base saturation is taken into account. The “ferrallithic” soils are thus further classified as being little, moderately, highly or very highly unsaturated.

3.7 Sugar industry

3.7.1 General

The Mauritius Chamber of Agriculture (2003) has reviewed the history and evolution of sugar cane cultivation in Mauritius. Fields with sugar cane have been a predominant feature of the landscape of Mauritius for more than two centuries. Sugar cane was one of several plant species of economic interest to be introduced in Mauritius under the Dutch administration. However, it was only in the following century that its cultivation was developed to a significant scale, together with other crops such as cotton, indigo, coffee and spices as the island started its economic development under French rule. Sugar cane proved to be the crop best suited to the local climatic, soil and topographic conditions and was therefore grown on a commercial basis. It is now the single most important crop in Mauritius and presently occupies some 72 000 ha, which represents about 40 percent of the country’s total area (186 000 ha), and 85 percent of the cultivated area (87 000 ha, excluding forests). However, the success of sugar in Mauritius is attributable not only to the high adaptability of the sugar cane plant to local conditions but also, to a large extent, to the fact that the country has benefited from preferential trade agreements with the United Kingdom (UK) and later with the European Union (EU), thanks to its membership of the Commonwealth and then the African-Caribbean-Pacific (ACP) group of nations.

In fact, Mauritius has made the most of the advantages derived from these trade preferences, particularly the Sugar Protocol and, to a lesser extent, the Special Preferential Sugar (SPS) Agreement. The Sugar Protocol, which was initially attached to the Lomé Convention and later on the ACP/EU Cotonou Agreement in 2001, has allowed duty free access for fixed quantities of ACP sugar at a guaranteed price into the EU market. By providing Mauritius with a predictable and stable source of earnings over the years, the Sugar Protocol has played an essential role in developing the local sugar industry and fostering the country's economic diversification. The revenues derived from these sugar exports have been re-invested into the sugar sector and into other economic activities, such as manufacturing, tourism and finance, which have today developed into major pillars of the economy of Mauritius. Nevertheless, sugar is still a major foreign currency earner and will remain an important sector of the economy for quite some time, and will continue to play a vital role in the socio-economic fabric of Mauritius.

3.7.2 Present status

3.7.2.1 Gross domestic product

Over the years, the share of sugar production in the economy of Mauritius has, in relative terms, dwindled and is expected to reach 3.5% of the gross domestic product in 2004 (from 25% in the 1970's) as compared to 22% for manufacturing industries, 18% for tourism and 19% for financing and business services. The reduced importance of the sector in the country's economy can be explained by the diversification of the economy of Mauritius with the rapid growth, during the 1980's and 1990's, of the manufacturing industry geared towards export, as well as the expansion of the tourism industry and the emergence of financial services, with consequential effects on employment and contribution to value added. The sugar sector has, in real terms, continued to bring additional revenue to the country and to the farming community at large. It is still an important contributor to the economy with sugar exports representing 19% of foreign exchange earnings.

3.7.2.2 Employment

In 2003, there were 11 sugar-milling factories and 23 sugar estates, with about 52% of the total sugar cane lands belonging to large sugar companies, which produce 55% of the total sugar. The remaining 48% of the sugar cane area belongs to some 28 000 individual planters. Direct employment in the sector stands at roughly 4% of total employment (around 20 000 persons) as compared to 29% in 1980. It is worth noting that employment in the sugar sector has decreased substantially with the introduction of a Voluntary Retirement Scheme (VRS) in 2001, which was taken up by some 7800 workers who opted for early retirement. Nevertheless, the sector is still a major source of employment as the 28 000 small planters, who are self-employed and operate on a part-time basis, are mainly involved in sugar cane cultivation and in the production of fresh vegetables. In most cases, their plot size does not exceed one ha.

3.7.2.3 Organizations

The milling and miller-planting companies of the sugar cane industry are grouped into the ***Mauritius Sugar Producers' Association*** to deal more effectively with problems such as those relating to employment, occupational health and safety in cane fields and mills, and training. As a result the industry has benefited from an improved operational efficiency and a safer work environment. Growers are grouped into several associations, namely the Mauritius Cane Growers' Association, the Mauritius Sugar Cane Planters' Association/Mauritius

Planters' Association, and the Mauritius Co-operative Agricultural Federation Ltd. All these associations form part of the ***Mauritius Chamber of Agriculture,*** founded in 1853 to promote and safeguard their interests. The ***Mauritius Sugar Syndicate,*** created to be the sole marketing agency for Mauritius sugar, contributes to make financial resources available on time to the planting community and ensures that the industry meets its obligation to supply the sugar to the European Union. As stated previously, all research and development work pertaining to the sugar industry is conducted by the ***Mauritius Sugar Industry Research Institute***, which is funded by a cess levied on all sugar produced.

Government organizations dealing with the sugar cane industry comprise ***The Mauritius Sugar Authority*** established in 1984 to promote and maintain the efficacy, development and viability of the sugar cane industry and thus to advise the Government on policies to be followed with regard to the sugar cane industry. ***The Cane Planters' and Millers' Arbitration and Control Board*** controls the milling of canes and the manufacture of sugar and assesses the quantity of sugar and by-products accruing to growers and millers. It should be remembered that, like any other agricultural venture, sugar cane production stands vulnerable to the vagaries of climate. To ensure that planters are not left totally resourceless in case of crop failure, the ***Sugar Insurance Fund Board*** was created in 1946 to guard against losses due to cyclones, droughts, excessive rainfall and fire. The ***Sugar Industry Development Fund*** provides funds for the formulation and execution of projects aimed at increasing cane productivity. There is also a ***Sugar Planters' Mechanical Pool Corporation*** that hires out agricultural equipment to growers at reasonable rates.

3.7.2.4 Sugar markets

Mauritius is signatory to the Sugar Protocol since 1975 and to the Special Preferential Sugar (SPS) Agreement since 1995. These two agreements regulate sugar trade between ACP countries and the EU and form an integral part of the EU Sugar Regime. The Sugar Protocol provides duty free access to the EU market for fixed quantities of sugar exported from 19 ACP suppliers, at a guaranteed price of 523.70 Euros c.i.f. per t. While the Protocol is of indefinite duration and has a "legal life of its own", the SPS Agreement has a limited duration and will last until the expiry of the existing EU Sugar Regime in June 2006. The guaranteed price obtained under the SPS Agreement represents 95% of that under the Sugar Protocol, i.e 496.80 Euros per t. Practically all the sugar production of Mauritius is exported to the EU under the Sugar Protocol (507 000 t yr^{-1} till 2008) and the SPS Agreement (around 25 000 t in 2003). The latter quantity is expected to decrease in the following years until it is completely eliminated by 2008.

Next to the EU market is the United States market. Mauritius exports some 12 000 to 15 000 t yr^{-1} under the US Tariff Rate Quota (TRQ), which is opened to some forty countries. The share of Mauritius under the US TRQ represents 1.2% of the total US yearly import. Domestic consumption of sugar in Mauritius is about 40 000 t yr^{-1} of which some 15 000 t are for industrial use and 25 000 t for direct consumption. The little that remains is sold on the world market (Figure 3.5).

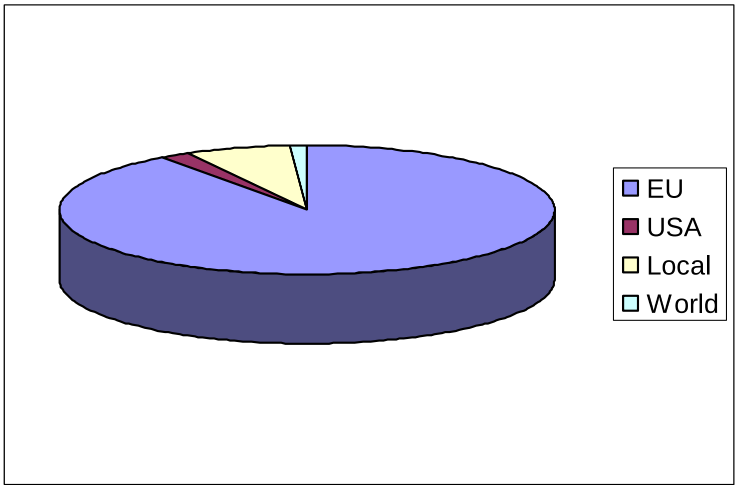


Figure 3.5 Markets for sugar produced in Mauritius (Mauritius Chamber of Agriculture, 2003).

3.7.3 The future

In the context of the new world economic order, the sugar industry of Mauritius needs to be competitive to survive. Indeed, in view of the threats and challenges ahead, namely the real risk of Mauritius sugar exports losing their competitive edge in a liberalized trade environment, a 5-year Sugar Sector Strategic Plan (SSSP) was launched by the Ministry of Agriculture, Food Technology and Natural Resources (2001), with the aim of providing the industry with the appropriate framework to improve its competitiveness and ensure its very survival. The sugar industry of Mauritius has embarked in major reforms at all levels, with centralization of milling activities, cost reduction, enhanced productivity, manpower rightsizing, the optimal use of cane sugar resources, well-planned diversification activities and the creation of new opportunities. Several targets need to be achieved by the end of the implementation period, the main ones being:

- Ensuring that export market commitments are fulfilled.
- Maintaining the sugar production target of 620 000 t yr^{-1}.
- Achieving substantial reduction in costs of production.
- Generating as much electricity from renewable sources, in particular bagasse.
- Adding value to the industry’s output through product diversification such as special sugars, electricity, ethanol, molasses and “rhum agricole”.
- Ensuring a more efficient and judicious use of land and water resources.
- Developing research, so as to fully tap the benefits deriving from biotechnology, biotics and cane biomass.

3.7.4 Research and development

The successful achievement of the objectives as spelt out in the SSSP will depend for a large part on research development. In this respect, the role of Mauritius Sugar Industry Research Institute (MSIRI) will be crucial. Autrey (2004) has reviewed the contribution of this body to the advancement of the sugar industry in Mauritius, and mapped out the way for its future. The MSIRI was established as a Statutory Body by Government Ordinance no. 9 of 1953, and has been responsible for all research associated with the sugar industry since that date. In terms of the Ordinance, its function was "to promote by means of research and investigation the technical progress and efficiency of the sugar industry". It has been in existence for more than half a century and is well recognized for its achievements, a few of which will be detailed hereafter:

- MSIRI's cane breeding program has led to the production of some 59 new varieties, i.e. an average of more than one new variety per year.
- An understanding of the stages of floral development at cellular level and factors controlling flowering has been achieved, thereby revolutionizing sugar cane breeding worldwide.
- The foliar diagnosis technique developed at MSIRI has been adopted worldwide for the monitoring of fertilizer recommendations.
- All pest and disease outbreaks have been controlled by biological or genetic means, without resort to pesticides, except in a few limited circumstances.
- In environment protection, it has been proven that fertilizers and herbicides used in the sugar industry do not contaminate the country's rivers and groundwater.

For the future, Autrey (2004) believes that MSIRI's expertise will be needed to help the sugar industry achieve its twin objectives of raising productivity and reducing production costs. Its main activities will focus on biotechnology, irrigation, mechanization, resource management, food technology and co-products, as well as some non-sugar crops. It will have to use new technologies to achieve these goals, while continuing to produce new varieties and ensuring that adverse factors do not compromise the development of the industry. The long-term vision of MSIRI is to help transform the sugar industry of Mauritius into an industry of renewable biomass, with the valorization of all the components of the biomass produced by the cane plant.

3.8 Conclusion

Mauritius is a small island of volcanic origin, but with great diversity in terms of climate and soil. Most of its original vegetation has disappeared as its increasing population has made optimum use of the available land. Today, the island is covered with sugar cane fields and the sugar industry remains a major component of the national economy, even though its influence has been waning. The land is still fertile and can keep on producing sugar cane with the correct application of water and fertilizers, and with the use of proper cultural operations.

However, several challenges lie ahead for the sugar industry. It must increase its productivity and reduce its costs to remain economically viable in the long-term. To achieve this goal, it must reduce its manpower and rely more heavily on the use of machinery. It must find other sources of income, which can be achieved through the sale of electricity produced from bagasse, through an optimized use of its available land, or even through the enhancement of the value of its by-products.

Should the sugar industry lose its economic viability, a major problem would arise with respect to land use. About half of the island is currently devoted to sugar cane cultivation. The cultural practices associated with this crop mean that the soil is kept under some form of cover for the better part of eight years, thereby protecting it from erosion. If cane were to be removed, what would be the effects on the environment? Alternative uses for the land would have to be found and the consequences of such changes cannot be foreseen. Cane has been grown in Mauritius for more than 350 years and is still the one crop that has stood the test of time.

CHAPTER 4

MATERIAL AND METHODS

4.1 Comparative studies

In order to establish the effects of manual sugar cane production practices on soil quality, the properties of pristine land must be compared to those of sugar cane land. Fields have to be selected to represent these two conditions, namely fields that have never undergone any form of cultivation and those that have been cropped manually with sugar cane for a relatively long period. Fields of this nature were selected carefully based on reliable information obtained from sugar estates.

Given that sugar cane production is expected to be economically viable only where mechanized production practices are introduced, these kind of land can be considered to be representative of the future for sugar cane production. Mechanized harvest requires the land to be relatively flat and rock-free, which is often not the case in several areas of Mauritius. In such cases, fields are subjected to derocking and land grading to render them suitable to mechanized harvesting. Thus, with respect to establishing the effects on soil quality of adopting sugar cane production practices such as derocking, land grading and mechanized harvesting, a comparison must be made between non-mechanized sugar cane fields, and fields which have been derocked, land graded and where sugar cane is mechanically harvested. Based on reliable information supplied by sugar estates, these kind of fields were selected.

The two types of comparisons, between native and sugar cane cultivated lands where the operations are still manual, and between mechanized and non-mechanized sugar cane fields, need to be extended to all five major soil groups of Mauritius. In this way, an indication can be obtained whether any change in soil quality as a result of sugar cane production would differ among the major soil groups used for sugar cane production. The five soil groups do not all occur in each of the three climatic zones of the island.

4.2 Choice of sites

There are five important soil groups in Mauritius based on the 1962 Soil Map (Parish and Feillafé, 1965) of the island, namely the Low Humic Latosol, Humic Latosol, Humic Ferruginous Latosol, Latosolic Reddish Prairie and Latosolic Brown Forest soils. These five major groups make up 87% of sugar cane lands in Mauritius and cover most of the range of soils and climate that exist over the island. One representative site per soil group has been selected for the study (Table 4.1).

Table 4.1. Study sites representing the five major soil groups of Mauritius

Study site	Climatic zone	Soil group	Area (ha)
Richeterre	Sub-humid	Low Humic Latosol (L)	30 455
Beau Champ	Humid	Humic Latosol (H)	9 640
Mon Désert Alma	Super-humid	Humic Ferruginous Latosol (F)	21 220
Médine	Sub-humid	Latosolic Reddish Prairie (P)	37 010
Savannah	Super-humid	Latosolic Brown Forest (B)	30 615

For each soil group, fields with different cropping histories were identified, each cropping history being deemed to be equivalent to a treatment. Thus, for the five soil groups, there were between three and five treatments under study, depending on cropping history (Table 4.2).

There were only three sampling categories within the H, B and F soil groups at Beau Champ, Savannah and Mon Désert Alma respectively. At Richeterre, the soils that had not been prepared for mechanized operations were further sub-divided into “old” (> 50 years) and “new” (< 25 years) fields, thus giving four treatments in the L soil group. This sub-division between “old” and “new” fields was also possible at Médine where soils under mechanized treatments were sub-divided into two categories, namely recent derocking and grading (within the last 3 years) or early derocking and grading (at least 10 years ago). Five treatments were thus identified in the P soil group.

Table 4.2. Treatments studied for five soil groups

Soil group	Treatment				
	1	2	3	4	5
L	●	●	●	●	
H	●	●		●	
F	●	●		●	
P	●	●	●	●	●
B	●	●		●	

Treatment 1: Pristine soil (natural forest or pasture)

Treatment 2: Old cane soil (>50 years under cane), no derocking or land grading

Treatment 3: New cane soil (<25 years under cane), no derocking or land grading

Treatment 4: Cane soil recently derocked and graded for mechanization (<3 years)

Treatment 5: Cane soil derocked and graded for mechanization (>10 years)

4.3 Sampling procedure

To account for possible spatial variability, four samples were taken from three fields with the same cropping history, thus giving twelve replicates per treatment. For each selected field, a one-ha zone was earmarked, within which four representative 50 m^2 sampling plots were chosen, at least 20 m distant from the edge of the field and other possible unrepresentative sites, e.g. close to irrigation risers. Two trenches were dug within each plot, thus giving a total number of eight trenches for each field. Soil samples from the same depth for each pair of trenches were bulked to give a representative sample for each plot (Figure 4.1).

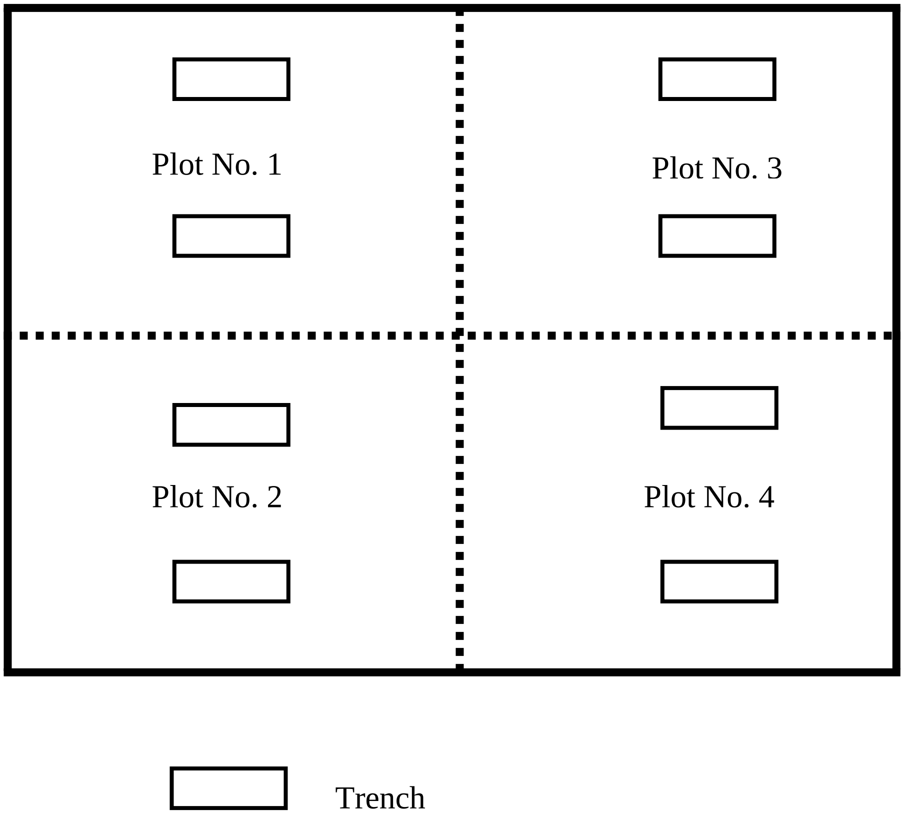


Figure 4.1. Pairing of trenches for bulking of samples (plan view)

Each trench was 150 cm long, 30 cm wide and 50 cm deep. Since cane rows are spaced 150 cm apart, this procedure ensured that soil underneath both cane row and inter-row was available for sampling. Soil was sampled from each trench in 4 layers, namely 0-5, 5-15, 15-30 and 30-50 cm. For each layer, two sub-samples were taken from both faces of the trench so as to cover as large an area as was possible (Figure 4.2). The four sub-samples obtained in this way were mixed to give a composite sample representative of the trench, and as stated before, the composite samples from each pair were mixed to give the sample for the plot.

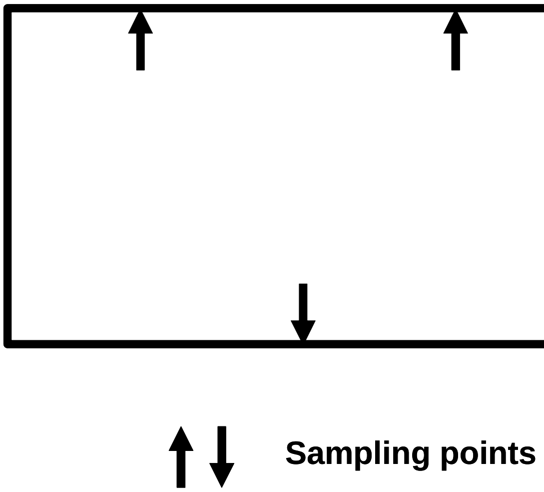


Figure 4.2. Soil sampling procedure from trench wall (plan view)

4.4 Soil quality parameters

Research work in sugar cane-producing countries such as Australia and South Africa has shown that a range of biological, chemical and physical soil properties are affected by sugar cane production. These properties are thus indicators that must be monitored to determine whether soil quality is affected. The following are the quality parameters for the sugar cane soils of Mauritius, namely:

1. Biological parameters - Organic matter and microbial biomass
2. Chemical parameters - pH, cation exchange capacity and concentration of exchangeable bases
3. Physical parameters - particle size distribution, aggregate size distribution, water stability of aggregates, bulk density, plant available water and stabilized infiltration rate.

4.5 Methodology for determination

4.5.1 Organic matter

The organic carbon and total nitrogen contents of the soils were measured as indicators of organic matter. A concise description of the procedures used follows.

As basalt is the parent material for most of the soils in Mauritius, the latter are non-calcareous and the measured amounts of carbon are solely of organic origin. The organic carbon content of the soils was determined in the laboratory through partial oxidation using the modified Walkley-Black procedure as described by Anderson and Ingram (1993). In this procedure, soil organic carbon was partially oxidized by treating 0.5 g of finely ground (<0.25 mm) air-dried soil with 10 ml of 5% potassium dichromate solution acidified with 20 ml concentrated sulphuric acid. After completion of this oxidation reaction, 50 ml of barium chloride solution was added and the mixture was centrifuged at 2500 rpm for 10 minutes. The supernatant was removed and the concentration of chromium ions in the reduced state within that supernatant was measured colorimetrically at 600 nm using a spectrophotometer. Since this concentration is directly proportional to the amount of organic carbon in the sample, the organic carbon content was deduced from chromium ion concentration.

The total nitrogen content of the soil was determined by Kjeldahl digestion followed by steam distillation and titration against sodium borate as described by Bremner and Mulvaney (1982). A 0.3 g sample of finely ground (<0.25 mm) air-dried soil was gradually heated to 150^{o}C in a block digestor with a mixture of concentrated sulphuric acid, salicylic acid and sodium thiosulphate till it reached a brownish green colour. Thereafter, 2 g of a catalytic mixture of Na_2SO_4, $CuSO_4.5\ H_2O$ and Se was added, and the whole mixture heated to 325^{o}C. Through this process, the nitrogen in the soil was mineralized to ammonium-nitrogen, which was then steam distilled under alkaline medium, using 30 ml of 50% NaOH. Ammonia gas was produced and was trapped into a mixture of 10 ml 2% boric acid and Conway-Omalay indicator. The concentration of nitrogen was then determined by titration with standard 0.0025 M sulphuric acid.

4.5.2 Microbial biomass

The microbial biomass was measured in the laboratory using the chloroform fumigation-extraction method of Voroney *et al*. (1993). A 40 g sample of fresh soil, sieved through a 4 mm mesh, was fumigated with 25 ml chloroform ($CHCl_3$), sealed and placed under vacuum for 1 minute. Subsequently, the sample was placed in the dark at 25°C for 24 hours. The $CHCl_3$ vapour caused a flush of decomposition of the soil microbial population. The microbial biomass constituents released by $CHCl_3$ fumigation, in this case microbial C and N, were then extracted directly using 60 ml of 0.5 M K_2SO_4 solution on a sub-sample of 12 g soil. The amounts of C and N dissolved in the K_2SO_4 extract were determined by dichromate and Kjeldahl digestion respectively. The amount of microbial biomass C and N present in the soil sample were calculated by comparing extracted values of C and N from fumigated soil samples to values from unfumigated soil samples.

4.5.3 pH

The pH was determined electrochemically in the laboratory using a pH meter by measuring the potential of the hydrogen ion electrode in a suspension of 20 g soil in 50 ml distilled water against that of a calomel reference electrode (STASM, 2003). The pH meter was first calibrated using buffer solutions of pH 4 and 7.

4.5.4 Cation exchange capacity

The cation exchange capacity (CEC) of the soils was determined in the laboratory using unbuffered ammonium acetate (Peech, 1945). As a first step, 5 g of air-dried soil, sieved through 2 mm mesh, was leached with 1 M unbuffered ammonium acetate solution to displace its exchangeable cations, namely Ca, Mg, K and Na. The exchange sites of the soil were filled with ammonium ions while the excess ammonium acetate was leached out of the soil by passing 125 ml of 96% ethyl alcohol. The sorbed ammonium ions were finally displaced by eluting the soil with 200 ml of acidified sodium chloride solution (10% NaCl in 0.1 M HCl) and were determined quantitatively by back titration with standard 0.0025 M sulphuric acid. The soil CEC was calculated from the amount of ammonium sorbed in the soil.

4.5.5 Exchangeable bases

The concentration of individual exchangeable bases in the soil samples was determined using the leachate obtained in the first step of the procedure described for CEC determination in Section 4.5.4 (Peech, 1945). As stated in Section 4.5.4, the 1 M unbuffered ammonium acetate solution displaced the exchangeable bases present in the soil sample and these elements, namely Ca, Mg, K and Na, remained dissolved in the leachate. An atomic absorption spectrophotometer was used to measure the concentration of Ca and Mg in the solution. The concentration of K and Na was determined using a flame photometer.

4.5.6 Particle size distribution

The size distribution of individual particles in the soil was determined in the laboratory by particle size analysis. In this procedure, the soil aggregates were destroyed or dispersed into discrete units by chemical and mechanical means as described by Gee and Bauder (1986). The particles were then separated according to size limits by sieving (sand fraction) and sedimentation (silt and clay fractions). The sedimentation analysis relies on the relationship between settling velocity and particle diameter (Stokes' Law), the smaller particles taking longer to fall to the bottom of a suspension.

As organic matter is a powerful aggregating agent in the soil, the first step was to chemically remove it by heating 10 g of air-dried soil, sieved through 2 mm mesh, with 2 g sodium metabisulphite and 50 ml 10% H_2O_2. The oxidation process using H_2O_2 was repeated twice to ensure that all organic matter had been removed. Once this oxidation process was complete, the soil was dispersed by shaking with sodium hexametaphosphate and maintained in the dispersed state until sedimentation was completed.

The silt content was determined at 20^{o}C in a constant temperature room by pipetting a 20 ml sample from the suspension after the critical time required for the silt fraction. Similarly, the clay content was determined through pipetting at the critical time required for the clay fraction. All the remaining silt and clay were then removed from the suspension by siphoning and the remaining sand material was dried and passed through a 150 μm sieve to obtain the coarse sand and fine sand fractions.

4.5.7 Aggregate size distribution

The size distribution of the aggregates was determined in the laboratory by dry sieving of air-dried soil samples using a nest of sieves. Although a rotary sieve with multiple sieve sizes is the recommended technique (Kemper and Rosenau, 1986), a sieve shaker (Retsch AS200 Digit analytical sieve shaker) with a flat nest of sieves was used in this case since no rotary sieve was available.

The bulk soil was sampled and placed on a large tray, and allowed to air-dry in the shade. Prior to placing in the sieve shaker, the aggregates were gently passed through an 8 mm sieve. Thereafter, a 1.5 kg sample was shaken for 10 minutes on the sieve shaker to pass through sieve sizes of 4, 2, 1, 0.5 and 0.25 mm. The respective amounts of soil retained in the different sieves were then weighed, and the index of aggregate size distribution calculated as the geometric mean diameter, or GMD (Kemper and Rosenau, 1986).

4.5.8 Water stability of aggregates

The stability of aggregates in water was determined in the laboratory by determining the soil moisture characteristics of weathered and unweathered soil samples using the technique described by Haines (1930). A 20 g sample of air-dried soil aggregates in the size range 1 to 2 mm were placed on the ceramic plate of a Haines apparatus (a sintered glass Buchner funnel connected to a burette), and soil moisture characteristics derived through desorption curve of a saturated sample (Figure 4.3). The desorption process was repeated with a weathered sample, the weathering process consisting of a sudden saturation of the sample, which was left submerged for 24 hours prior to air-drying.

Differential curves (Figure 4.4) derived from the soil moisture characteristics were obtained to reflect the pore size distribution within the soil sample. An aggregate stability index was thereafter calculated from the respective slopes of moisture characteristics of the weathered and unweathered samples as outlined by Childs (1940).

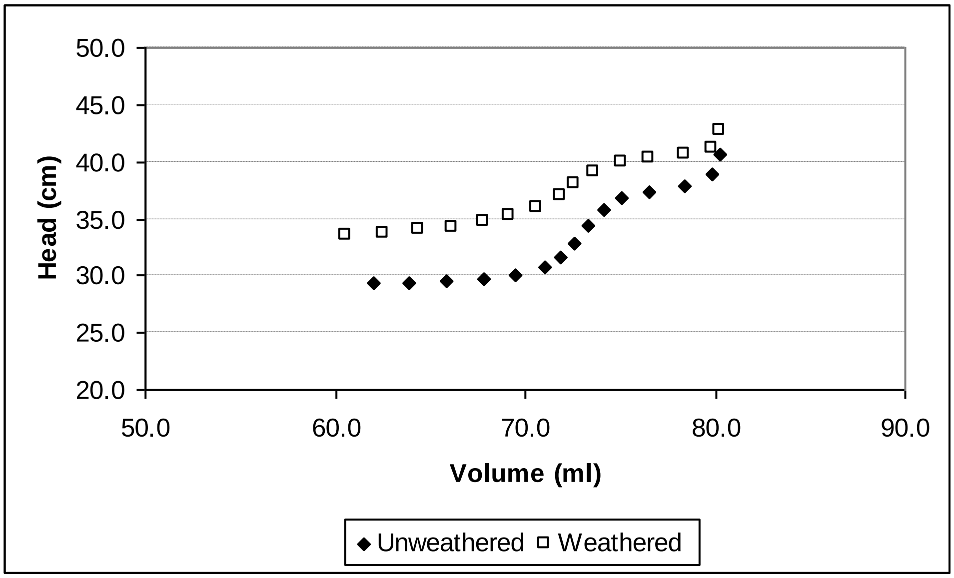


Figure 4.3 Desorption curves obtained using Haines apparatus

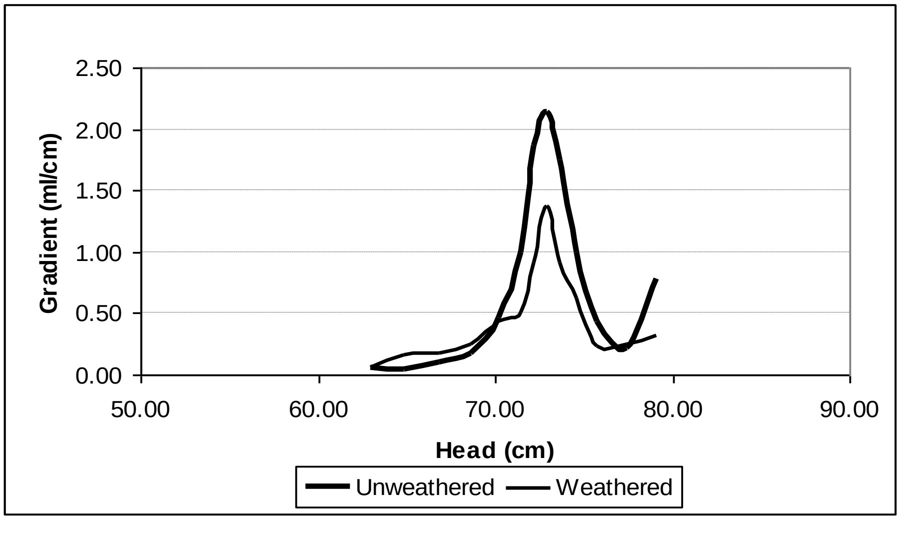


Figure 4.4. Differential curves derived from desorption curves

4.5.9 Bulk density

Bulk density determinations were undertaken *in situ* using the excavation method, essentially because the presence of stones within the profile at several locations prevents the use of the core method. In this procedure, a certain quantity of soil was excavated from the required depth in a 10 cm diameter hole, dried and weighed. A sand-funnel apparatus was used to measure the volume of the excavated material by filling the hole with sand of known volume per unit mass (Blake and Hartge, 1986). The volume of the excavation was then taken to be equal to the volume of sand dispensed.

The excavated soil samples were oven-dried at 105^{o}C for 24 hours and weighed. Thereafter, they were washed through a 2 mm sieve and any remaining stone was again oven-dried at 105^{o}C for 24 hours and weighed. Bulk density was calculated as the oven-dried weight of soil per unit volume. A correction was applied to this calculation when stones were found in the soil sample. The stone weight and volume were subtracted from the total weight and volume to give corrected values of the two parameters. The calculation for stone volume required the use of a standard bulk density of 2.65 g cm^{-3} for stones. The corrected bulk density was calculated as the corrected soil weight per unit corrected soil volume.

4.5.10 Plant available water

Soil moisture contents at field capacity (FC) and permanent wilting point (PWP) were determined in the laboratory on sieved air-dried soil samples using pressure plate and pressure membrane extractors as indicated by Klute (1986). A 25 g air-dried soil sample, sieved through 2 mm mesh, was placed on a pressure plate and saturated with water. It was then placed inside pressure extractors and a pressure of 15 kPa was applied for 24 hours, when equilibrium was reached and all excess water had been removed. The procedure was repeated with another sample, but under a pressure of 1500 kPa. The soil moisture content at equilibrium with 15 kPa was deemed to be the FC moisture content, while that at 1500 kPa was taken as the PWP moisture content. Plant available water (PAW) was then calculated based on values of FC, PWP, bulk density (BD) and soil depth using equation 4.1:

$$\text{PAW} = 0.1 \times (\text{FC} - \text{PWP}) \times \text{BD} \times \text{soil depth} \qquad (4.1)$$

where PAW is in mm; FC is in % in gravimetric terms; PWP is in % in gravimetric terms; BD is in g cm^{-3}; and soil depth is in cm.

4.5.11 Stabilized infiltration rate

The stabilized infiltration rate of the soil was determined in the field using the CSIRO disk permeameter described by Perroux and White (1988). After clearing a flat piece of land, some sand was placed as contact material and the permeameter placed on the sand. The apparatus was set such that a zero head was applied. The volume of water being absorbed by the soil was read off the scale of the permeameter at standard time intervals taken from a stopwatch, initially every minute for the first ten minutes, and subsequently every five minutes until the rate had stabilized. The volume reading was then converted to a height of water by dividing with the contact area. Infiltration rate was calculated as the difference in height of water (mm) per unit time (hour). The soil absorbed the water at a fast rate initially, the rate declining gradually to reach a constant value, namely the stabilized intake rate, as illustrated by Figure 4.5.

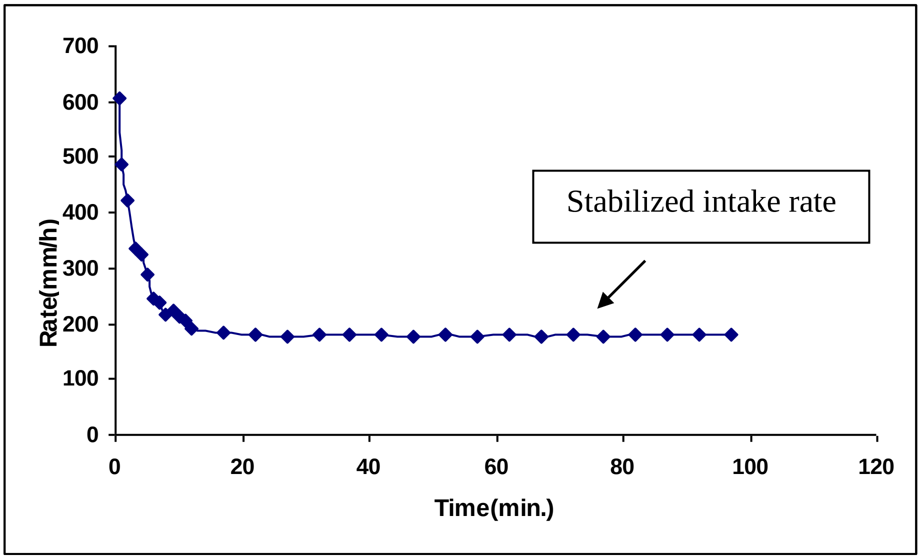


Figure 4.5. Infiltration curve derived from CSIRO disk permeameter test

CHAPTER 5

INFLUENCE OF SUGAR CANE PRODUCTION ON SOME SOIL BIOLOGICAL PARAMETERS

5.1 Introduction

The organic matter (OM) content in topsoil usually declines when land under native vegetation is cropped with sugar cane. This reflected in lower contents of either organic carbon (OC) and total nitrogen as reported by Van Antwerpen and Meyer (1996) for three different soil types at several sites in KwaZulu–Natal, South Africa. Henry and Ellis (1996) reported 8% and 26% decreases in OC and total nitrogen respectively in two soil types in North East Swaziland. In Australia, McGarry *et al*. (1996) noted that OC content was only 1.0% in the cane row as compared to 1.5% in an uncultivated soil. The SOM decline under sugar cane production was mainly caused by enhanced aggregate disruption to expose physically-protected organic material to microbial action when cultivated, and enhanced decomposition rates due to more favourable conditions of aeration, temperature and water content (Dominy *et al*., 2001). There were however also cases where SOM was found to increase under sugar cane. Such an increase had been observed in Australia by Bramley *et al*. (1996) and was restricted to the topsoil. They measured an OC content of 2.8% in the upper 5 cm of an “old” cane land, compared to 1.6% in the equivalent layer of a newly-converted cane land and suggested that it was the result of the beneficial effect of green cane harvesting / trash blanketing adopted at the site.

Where SOM content decreased after introduction of sugar cane, the rate of decline was found to be initially fast before becoming much slower after a few years prior to attaining a new equilibrium situation. This has been illustrated by Dominy *et al*. (2001) who showed that in South Africa, soil OC content went through a fast decline during the first ten years and attained an equilibrium level within thirty to fifty years. They hypothesized that the equilibrium level was dependent on the soil’s ability to stabilize OM and on the amount, quality and distribution of the plant residues. Measurements of the fast initial decline in Papua New Guinea showed a rate of 0.14% per year over the first seven years of cultivation (Hartemink, 1998b). The slower long-term decline rate was found to be 0.04% per year over fifty years for one soil and 0.01% per year over thirty years for another soil in South Africa (Qongqo and Van Antwerpen, 2000). Even though topsoil OC content tended to fall with the introduction of sugar cane, very little change has been observed in its chemistry (Skjemstad *et al*., 1999).

A downward transfer of OC has been noted with sugar cane cropping, this process being ascribed to the secondary effects of OC-rich topsoil being mixed with the subsoil during land preparation (Masilaca *et al*., 1986). A similar OC-enriching effect of the subsoil could be achieved by ploughing in the residues of break crops (McGarry *et al*., 1996). However, subsoil OC content has not always been reported to increase with sugar cane cropping. There were instances where there was no change (Henry and Ellis, 1996) or even a drop (Van Antwerpen and Meyer, 1996) in subsoil OC content. Residue management seemed to play a major part in the evolution of soil OC content. Trash burning removed crop residues and has been proven to substantially reduce SOM content (Wood, 1985), while green cane harvesting and trash blanketing had an opposite effect (Bramley *et al*., 1996, Graham *et al*., 1999). Furthermore, even if total OC decreased, the light carbon fraction remained in proportion with total OC in soil with cane trashing (Skjemstad *et al*., 1999).

In parallel with the decrease in SOM content, sugar cane cultivation also led to a marked decline in soil microbial biomass, possibly because of pesticide usage (McGarry *et al*., 1996). This decrease in microbial biomass was even more pronounced than that of OC, but the trend was similar, a fast rate during the first ten years and a new equilibrium level being attained within twenty years (Dominy *et al*., 2001). This trend was explained by the fact that the labile fraction of the OM was preferentially lost when the soil was cultivated; as a result, a long-term cultivated soil was able to support only a proportionately smaller microbial community than an undisturbed one, in spite of the crop residues that were added. Upon sugar cane cultivation, microbial quotient was thus shown by Dominy *et al*. (2001) to decrease to 1.37%

and 1.46% in two soils from a common initial level of 2.60%. However, this trend could be reversed under specific circumstances, for instance when trash was conserved at harvest (Graham *et al*., 1999). The annual fertilizer applications in the cultivated fields led to an increased return of organic residues to the soil, which in turn led to a higher soil microbial population.

In this chapter, the effects of sugar cane cropping on some biological properties of the major soil groups of Mauritius are reported. Two indicators of biological quality, organic matter and microbial biomass, were assessed through three parameters, namely carbon, nitrogen and C/N ratio. The changes resulting from manual and mechanized sugar cane cropping practices on all five major soil groups are presented. In addition, the effects of time under manual and mechanized sugar cane cropping practices for selected soil groups are also dealt with.

5.2 Procedure

5.2.1. General

The soil biological quality parameters that have been measured were organic carbon, total nitrogen, biomass carbon and biomass nitrogen. A complete description of the methodology used to determine these four parameters was given in Chapter 4. All organic matter measurements were made in the laboratory on samples sieved through a 2 mm mesh since this fraction is defined as soil (Soil Survey Staff, 1975). Air-dried samples were used for the organic C and total N determinations. Hence the concentration of organic C and total N were directly derived from laboratory measurements and expressed in terms of percentage on a dry weight basis. However, fresh samples sieved through a 4 mm sieve were used for the biomass C and biomass N determinations. Thus for microbial biomass C, the amounts present were calculated from Equation 5.1 after determination of biomass C concentration, and were expressed in t ha^{-1} over 15 cm depth only, since sampling for biomass parameters was confined to the upper 15 cm zone. As shown by Dominy *et al*. (2001), microbial biomass content was negligibly small below 15 cm and changed very little with cropping, so there was no need to measure biomass deeper than 15 cm. Equation 5.1 was also applied to biomass N to calculate the amounts of N present in the microbial biomass.

M_{biomC} = 0.1 x [biomC] x BD x (1- stone fraction) x depth of layer (5.1)

where M_{biomC} is biomass carbon in kg ha^{-1}; [biomC] is concentration of biomass carbon in mg kg^{-1}; BD is bulk density in g cm^{-3}; Stone fraction is non-dimensional; and depth of layer is in cm.

Furthermore, the relative concentrations of C and N have been used to derive the carbon to nitrogen (C/N) ratio for both the whole soil and the microbial biomass as per Equation 5.2.

C/N ratio = [C] / [N] (5.2)

where [C] is % concentration of carbon and [N] is % concentration of nitrogen.

5.2.2 Data processing and analysis

Since any individual measurement would lack precision, multiple measurements were required, even though none of the measurements was likely to be more precise than the others. However, it was expected that this group of values would cluster around the true value being measured. A single data point, the mean, or average value, was thus computed to represent this distribution of data values. It described a middle point, or central tendency, about which the data points varied. The variation in the data was described by the standard error of the mean, normally abbreviated to SE, which was effectively the standard deviation of the means (Streiner, 1996). This standard error was calculated from Equation 5.3.

$SE = SD / \sqrt{N}$ (5.3)

where SE is standard error; SD is standard deviation; and N is the number of samples.

To obtain the SE value, the SD had first to be calculated. This was achieved by using Equation 5.4.

$$SD = \sqrt{}\ \Sigma\ (X_i - M)^2 / (N - 1) \qquad (5.4)$$

where SD is standard deviation; X_i is an individual data point; M is the mean; and N is the number of data points.

At all sites, a total of twelve individual samples or measurements were taken per treatment. Furthermore, these twelve replicates were repeated for each of the sampling depths. Thus, each group of twelve individual data points was used to compute the average value and its standard error, i.e. N = 12 in Equations 5.3 and 5.4. The computation of the standard error of the soil and biomass C/N ratio had required additional calculations using Equation 5.5.

$$SE = (av_C/av_N) \text{ x } [(se_C/av_C)^2 + (se_N/av_N)^2]^{½} \qquad (5.5)$$

where SE is standard error of C/N ratio; av_C is average value of C concentration; av_N is average value of N concentration; se_C is standard error of C concentration; and se_N is standard error of N concentration.

5.2.3 Data presentation

The data sets were processed using the Microsoft Excel program in Windows XP. This program was used for both calculations of mean and standard error, and for subsequent graphical presentation of the data. Thus, the standard deviation was calculated using the STDEV function in the program. Standard error was calculated by dividing the standard deviation obtained by 3.46, i.e. √12. The graphical functions of Microsoft Excel were then used to plot the average value and standard error of each treatment.

For concentration of organic C, total N and C/N ratio in the soil at different depths, the soil layer was on the y-axis while the measured parameter was on the x-axis. The data for each soil layer has been represented as one single point, taken to be in the middle of the layer concerned, giving a line graph with horizontal error bars showing the standard error for each point. On the other hand, the microbial biomass C and N content, and its C/N ratio, have been represented by bar charts, with vertical error bars representing the standard error.

The graphs have been interpreted in the following way: where the error bars for two treatments did not overlap, the difference between the two treatments has been taken to be significant. Otherwise, there was no significant difference. The advantage of this form of representation was that it summarized the whole data set together with its existing variability in one graph, and any significant difference was immediately visible. There were three sets of graphs for each parameter. The first set included the native, manual and mechanized situations. Effects of sugar cane cropping have been discussed by comparing the native with the manual situation, while those of mechanization were discussed by comparing the manual with the mechanized situation. The second set pertained to the comparison between “old” (> 50 years) and “new” (< 25 years) cultivations, as defined in Section 4.2, and made it possible to determine the effects of time under cultivation. The third and final set compared mechanized soils that have undergone recent derocking and grading (within the last 3 years) with those that were subjected to early derocking and grading (at least 10 years ago) to determine the effects of time under mechanization.

5.3 Results and discussion

5.3.1 Organic matter

5.3.1.1 Effects of manual and mechanized sugar cane cropping practices on organic matter

The humid H soil had the highest OC concentration under native vegetation while the L soil had the lowest concentration (Figure 5.1). Compared to the P, L, B and F soils, the H soil had a much higher OC concentration in its topsoil (defined as the 0 - 15 cm layer). However, the difference in concentration became smaller in the subsoil (defined as the 15 - 50 cm layer).

The H soil also had the highest total nitrogen concentration under native vegetation (Figure 5.2). There were major differences with respect to total N in the four other soils since the sub-humid P and L soils had higher topsoil total N contents than the super-humid F and B soils. The C/N ratio of the soil was dependent on the climatic zone. Thus, the sub-humid P and L soils had a lower C/N ratio under native vegetation than the humid H and super-humid B and F soils (Figure 5.3). The highest C/N ratio was found in the super-humid F soil, where it reached 14 for the whole profile.

In the rocky soils, there was a significant fall in OC concentration with sugar cane cropping in the P topsoil and a significant rise in the B subsoil. In the rock-free H, F and L soils, OC concentration decreased with sugar cane cropping in the topsoil, but was counter-balanced by an increase in the subsoil. The decrease in SOM with sugar cane cropping in the P soil was confirmed by the significant fall in total N in its topsoil, while the SOM-enhancing effect of sugar cane cropping was confirmed in the B soil by a significant rise in total N in both topsoil and subsoil. In the H and F soils, total N followed the same trend as OC, with its concentration decreasing with sugar cane cropping in the topsoil and increasing in the subsoil. In the L soil, total N decreased with sugar cane cropping in the topsoil but remained unchanged in the subsoil. The effects of sugar cane cropping on C/N ratio in soil were influenced by climatic zone. In the sub-humid zone, cultivation tended to raise C/N ratio as it was higher in sugar cane-cultivated soils than in virgin soils, even though the change was not significant in most cases. The opposite trend occurred in the humid and super-humid zones, where the cropped H, F and B soils had a lower C/N ratio than their virgin counterparts. The fall in C/N ratio was significant in the H topsoil, and in most of the profile of the F and B soils.

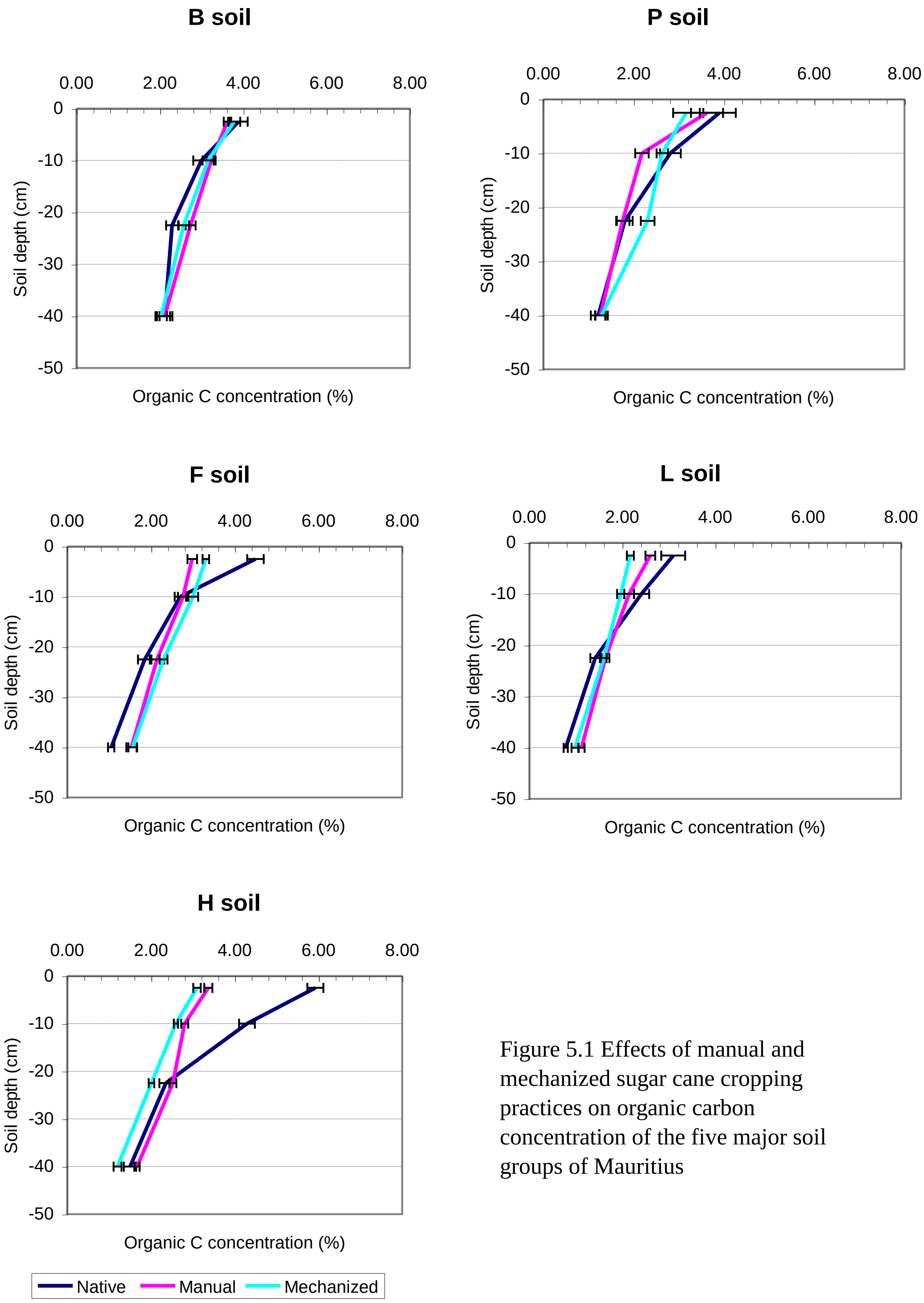


Figure 5.1 Effects of manual and mechanized sugar cane cropping practices on organic carbon concentration of the five major soil groups of Mauritius

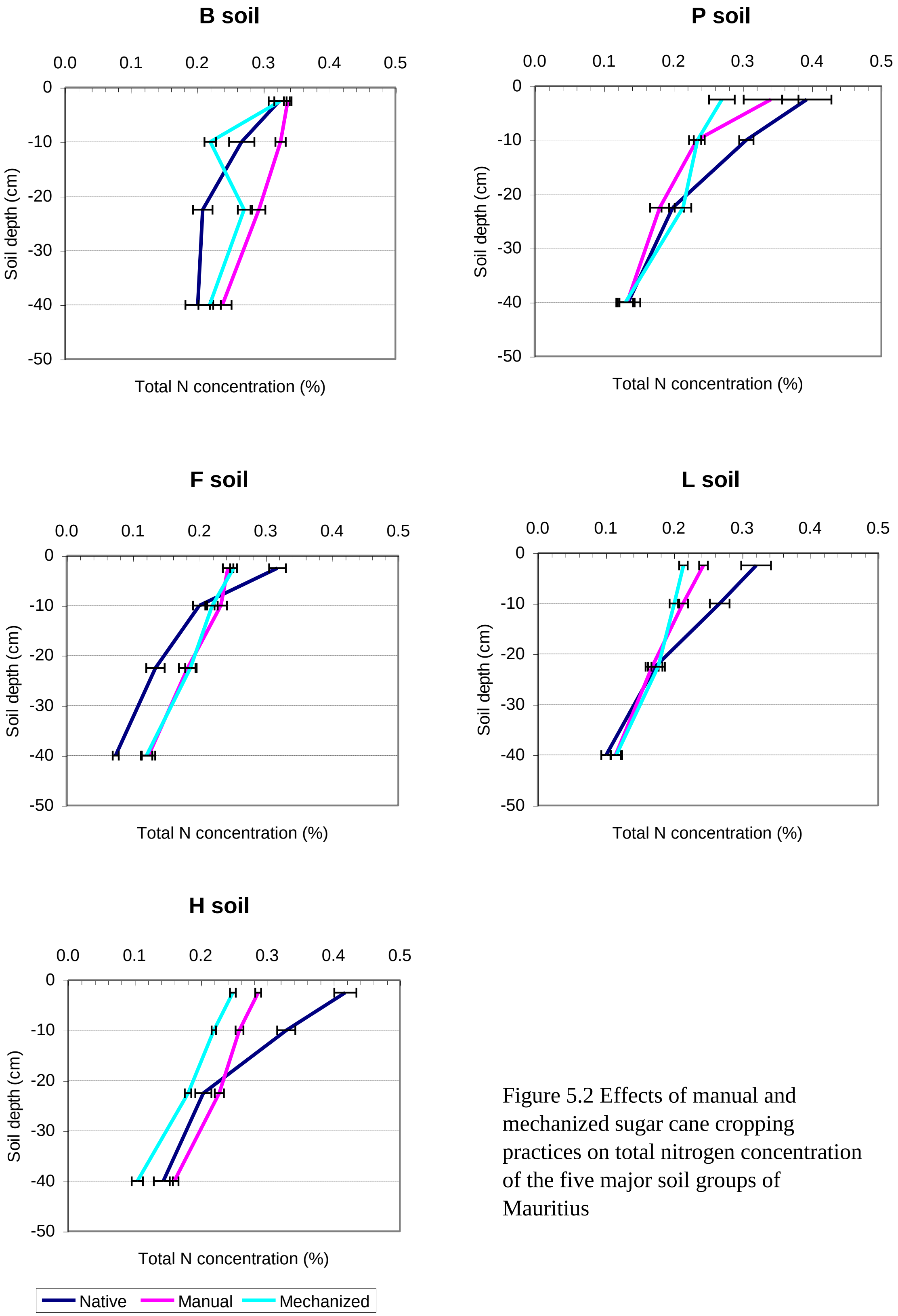
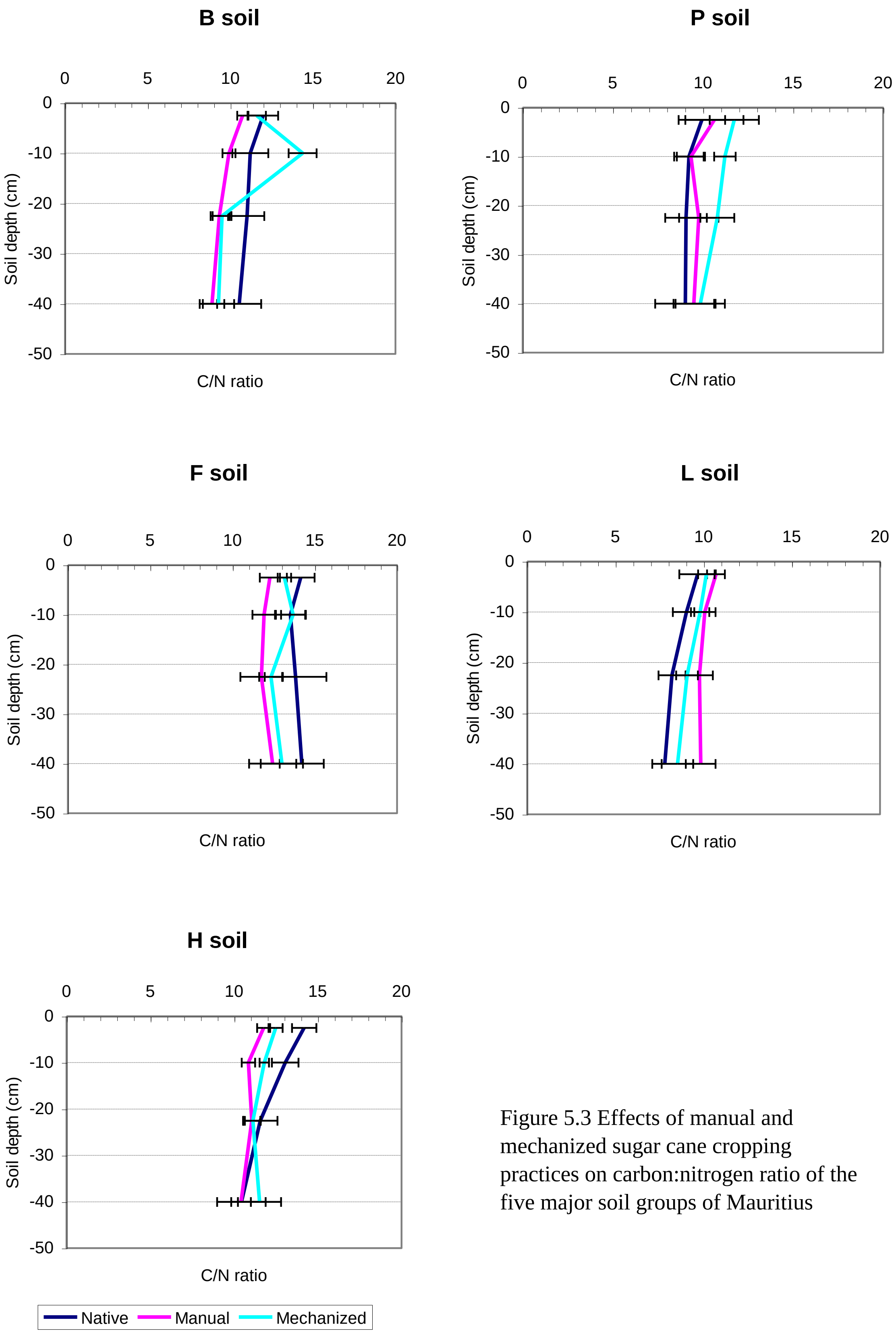


Figure 5.2 Effects of manual and mechanized sugar cane cropping practices on total nitrogen concentration of the five major soil groups of Mauritius



B soil

P soil

F soil

L soil

H soil

Figure 5.3 Effects of manual and mechanized sugar cane cropping practices on carbon:nitrogen ratio of the five major soil groups of Mauritius

The OC and total N concentrations in the mechanized fields of the super-humid F soil were not significantly different from those where manual operations were practised. In the super-humid B soil, adoption of mechanized practices led to a decrease in total N concentration while OC concentration remained unchanged. On the other hand, OC concentration decreased significantly with mechanized practices in the rock-free H and L soils. Total N concentration also declined significantly with mechanized practices in the H soil and in the L topsoil. The P soil was the only one whose OC and total N concentrations tended to increase as a result of the introduction of mechanized practices. The C/N ratio increased significantly with the adoption of mechanized practices in the P, H, B and F topsoils. C/N ratio decreased, but not significantly, in the sub-humid L soil.

One would normally expect SOM content to fall with sugar cane cropping for the reasons put forward by Dominy *et al*. (2001), namely enhanced exposure of hitherto protected SOM to microbial action and higher decomposition rates as a result of more favourable conditions. While this was true for the topsoil, there was also a trend for a higher OC and total N concentration in the subsoil by way of compensation. These observations have demonstrated that sugar cane cropping promoted the downward transfer of SOM in the profile as reported by Masilaca *et al.* (1986). This was a long-term process as soil tillage led to the mixing of the OM-rich topsoil with the subsoil and residues were further added to the deeper layers when the fields were prepared for planting. The higher OC and total N contents in the subsoil of the super-humid B and F soils were probably brought about by the return of OM to the soil as a result of green cane harvesting in the super-humid region. All the old leaves and green tops were retained *in situ* after harvest and arranged in alternate inter-rows, thereby providing a ready source of OM for the soil. In contrast, the fields from the sub-humid and humid zones were normally harvested after the cane had been burnt to get rid of the trash, a common practice in those areas for improving the harvesting efficiency of the labour. Hence, there was a lower return of carbonaceous material in the humid and sub-humid soils and the latter were therefore likely to have lower OM contents. This was the case with the P soil, which was the only one whose subsoil OC and total N contents did not increase. On the other hand, the L and H soils had increased amounts of subsoil OC with sugar cane cropping, showing that sufficient organic inputs had been produced to compensate for the losses. However, while total N concentration also increased with sugar cane cropping in the H subsoil, there was no difference in the L subsoil. Since OC increased and total N did not change, the effect of cropping was to increase the C/N ratio in the L subsoil. The fact that C/N ratio decreased with sugar cane cropping in the super-humid zone indicated that there was less undecomposed plant material than under virgin conditions. A likely explanation was that, with tillage, the turnover rate of OM was increased as the soil disturbance put the microbial population in better contact with the residues. In addition, tillage favoured aeration and exposure to sunlight, thereby increasing the rate of residue breakdown. In contrast, the higher C/N ratio in the sub-humid zones showed an increase in undecomposed residue with cultivation. As OM turnover rate would be expected to increase, the only explanation for such an observation was that there were more residues for decomposition in these cultivated soils than under virgin conditions. This higher residue content was caused by the additional biomass produced under irrigated sugar cane production as opposed to the sparse natural vegetation in these dry regions.

With the introduction of mechanization, particularly mechanized harvesting, the soil was often subjected to more disruption as the main objective in the land preparation was to smooth the field surface to create ideal conditions for operating the harvester. Given the disturbance, it was very likely that OM was affected negatively by the land preparation. This is what was noted in the L and H soils. On the other hand, there was likely to be much less disturbance in the super-humid F and B soils as land preparation was much less drastic in those soils. In fact, the time opportunity for large-scale mechanical operations is extremely limited in the super-humid region on account of the prevailing wet conditions. The OM content of these two soils was therefore not affected by the adoption of mechanized practices. The P soil was exceptional compared to the other four soils in that its OM concentration increased following the adoption of mechanized practices. This was not surprising if one considers the organic amendments that the sugar estate had added to its P soil following land preparation for mechanization. Indeed, substantial amounts of stillage slop and scum compost had been applied prior to planting, at rates of 20 and 5 t ha^{-1} respectively. The scum compost application was equivalent to 15 t ha^{-1} of fresh scum. Stillage slops contained 7 – 10% solids, of which 71% were organic in nature, such as reducing sugars, proteins and gums (Paturau, 1989). The scum compost also contained OM, such as sucrose, wax fat and fibre. These made up 10.0 to 17.7 % by weight of fresh scum (Paturau, 1989). Consequently a very large amount of OM was being applied to the P soils, resulting in an increased SOM content.

5.3.1.2 Organic matter and length of time during which sugar cane has been cropped manually

The concentrations of OC and total N were significantly higher in the P soil cropped with sugar cane for a long time compared to the recently cultivated one (Figure 5.4). In the L soil, OC concentration increased with time under cropping in the topsoil. Its total N concentration was mostly unaffected by time under cropping (Figure 5.4). The C/N ratio was slightly higher in the soils cropped with sugar cane for a long time compared to the recently cultivated ones in both P and L soils (Figure 5.4). However, this increase in C/N ratio was non-significant in the whole profile of the two soils.

These results indicate that OM content rapidly reached an equilibrium situation under sugar cane cropping in the L soil. In the P soil, the high degree of SOM accumulation with time was presumably a consequence of accumulation of OM from dry leaves and old roots after harvest, even with sugar cane burning. The provision of irrigation must have played a part in this accumulation, as the cultivated fields produced more biomass and therefore more residues to contribute to the build-up with time. The increase in OM concentration noted in the L topsoil was also probably caused by a temporal accumulation of residues.

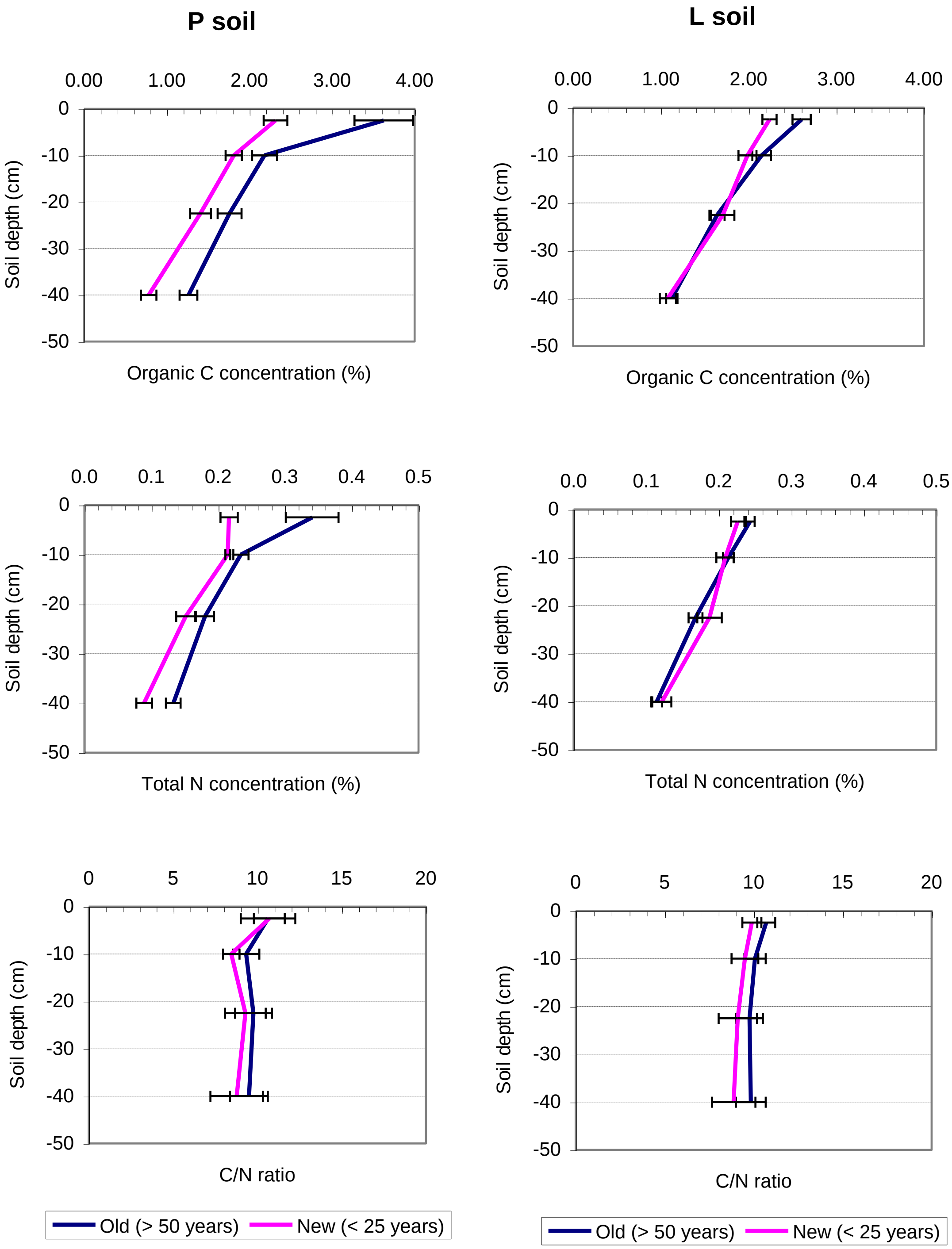


Figure 5.4 Effects of length of time under manual sugar cane cropping on organic C concentration, total N concentration and carbon:nitrogen ratio of the two major soil groups in the sub-humid zone of Mauritius

5.3.1.3 Organic matter and length of time during which mechanized practices have been adopted

The OC and total N concentration of soils tended to fall under long-term mechanized conditions as the two parameters were significantly lower in early mechanized fields than in fields recently mechanized (Figure 5.5). The C/N ratio stayed constant with time.

Such an OM decrease with time under mechanized conditions in the P soil was not surprising as the estate initially added very large amounts of OC-rich amendments to its soils immediately after land preparation. Afterwards, the soil slowly reached an equilibrium condition as there were no further external OM additions. There was thus an initial flush of OM in the recently mechanized fields, but OM content later decreased naturally as the microbial population attacked the more labile organic material. Eventually, the old mechanized fields reached a stabilized condition with the OC and total N concentration much lower than the initial values.

5.3.2 Microbial biomass

5.3.2.1 Effects of manual and mechanized sugar cane cropping practices on microbial biomass

Under native vegetation, the rocky P and B soils had the lowest amount of biomass C, slightly less than 500 kg ha^{-1} in the upper 15 cm (Figure 5.6). The rock-free L and F soils contained sligthly more biomass C, some 600 kg ha^{-1} in the upper 15 cm, but the highest content occurred in the humid H soil, where it attained 1.0 t ha^{-1}. The H soil also contained the highest amount of microbial biomass nitrogen, some 160 kg ha^{-1} (Figure 5.7). The super-humid F soil had a biomass N content in the order of 100 kg ha^{-1}, while the B, P and L soils had a biomass N content in the order of 40 to 60 kg ha^{-1}. The microbial C/N ratio was highest in the B soil, followed by the L soil, while the other three soils had very similar lower values (Figure 5.8). The relatively high values of the B and L soils could be attributed to their lower microbial biomass N.

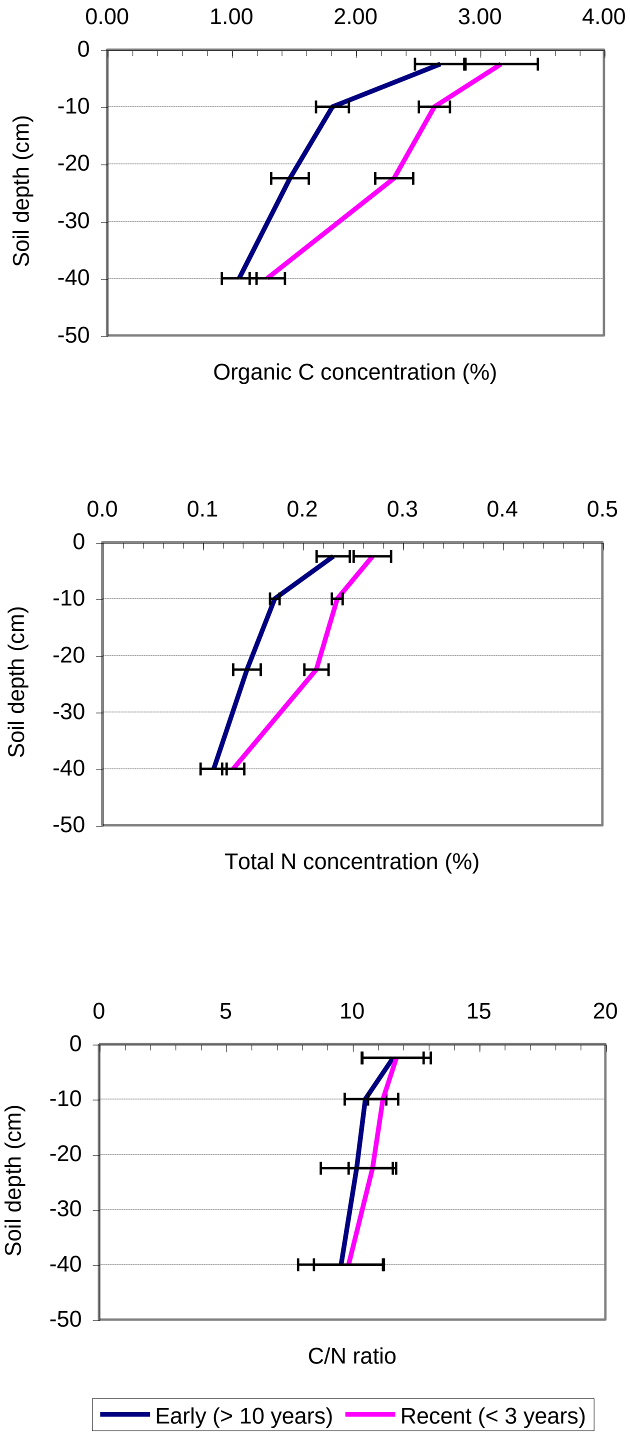
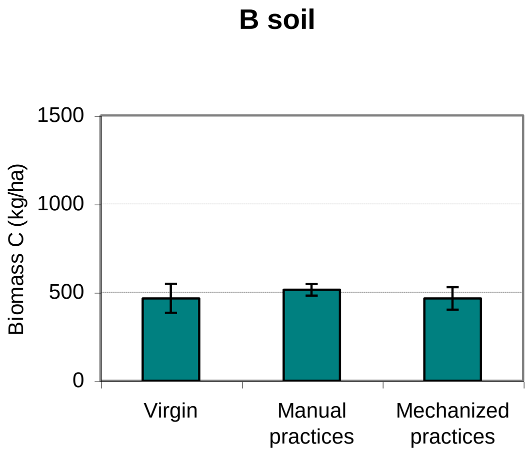
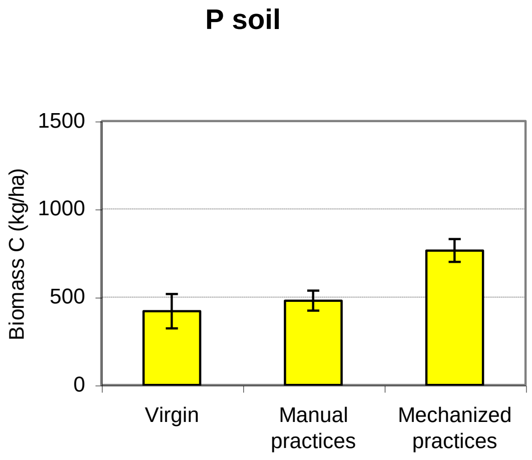
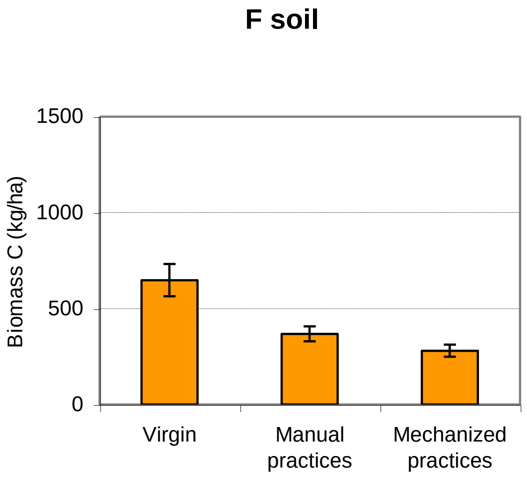
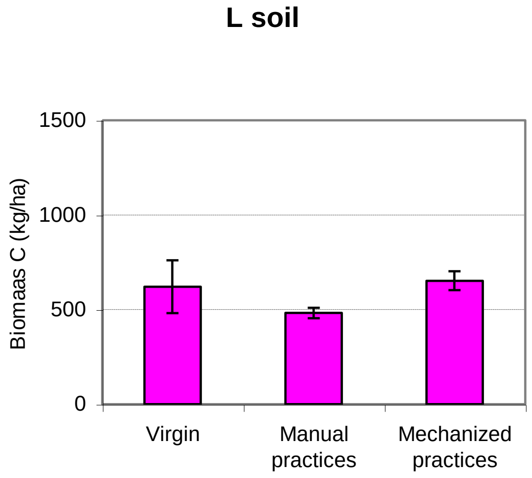


Figure 5.5 Effects of length of time for which mechanized practices have been implemented on organic C concentration, total N concentration and carbon:nitrogen ratio of P soil of Mauritius cropped with sugar cane









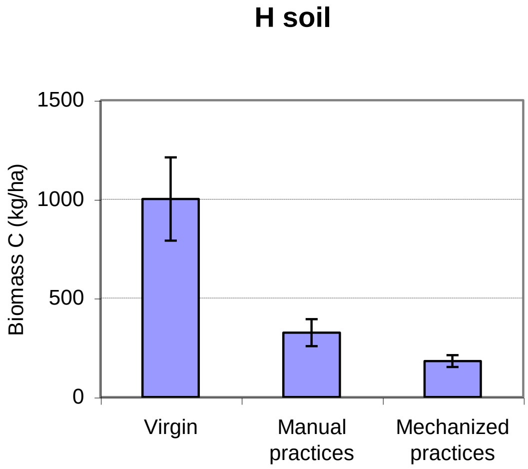


Figure 5.6 Effects of manual and mechanized sugar cane cropping practices on biomass carbon content (kg/ha over 15 cm soil depth) of the five major soil groups of Mauritius

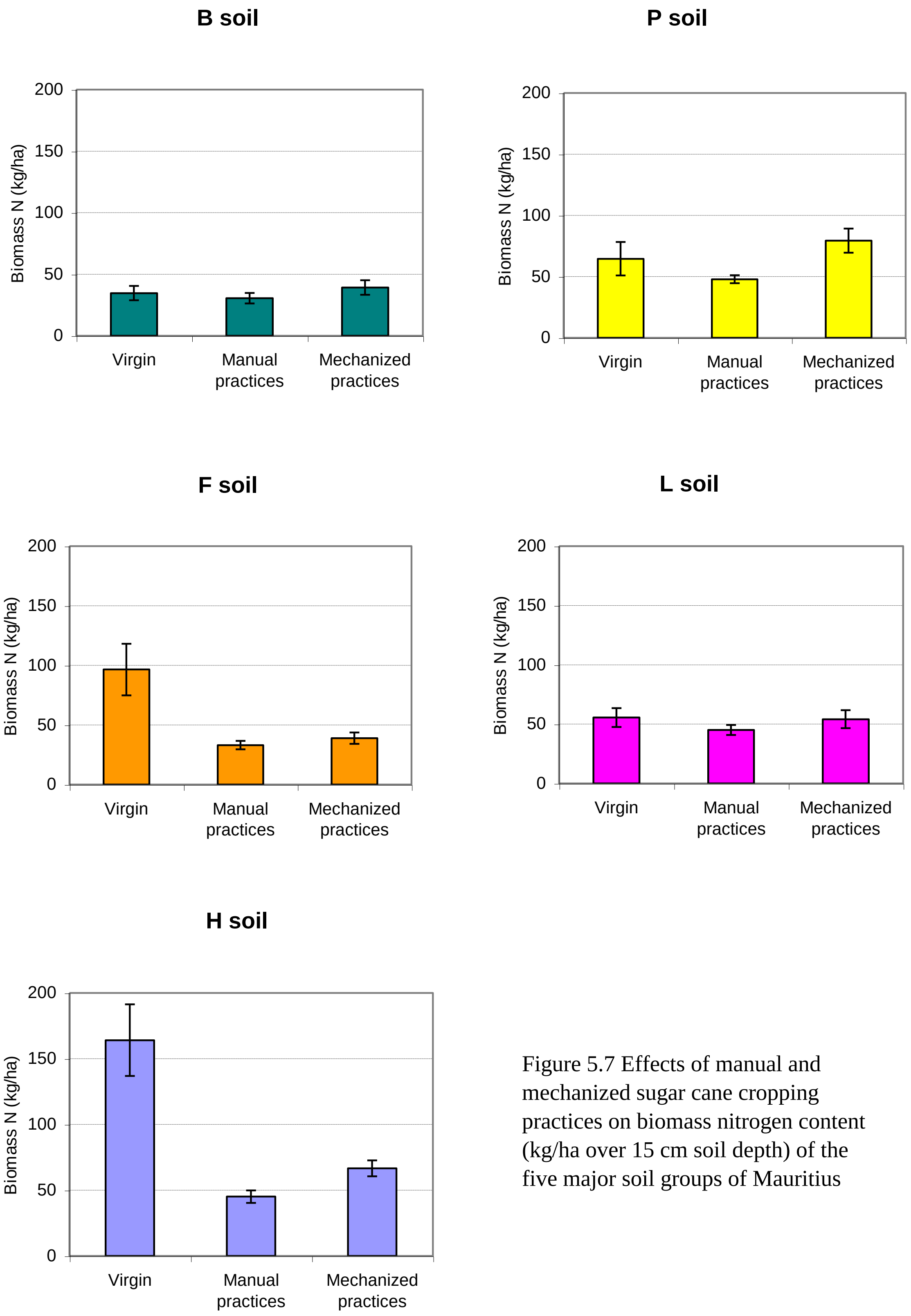
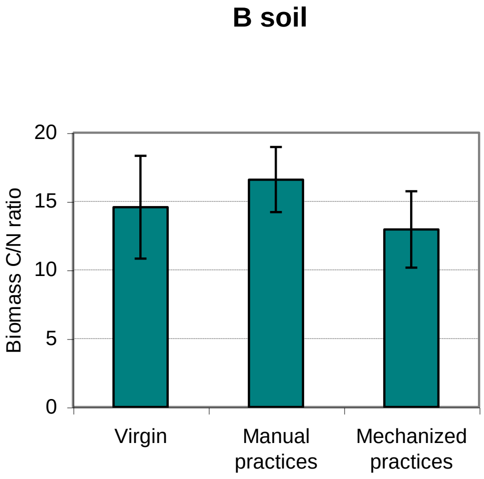
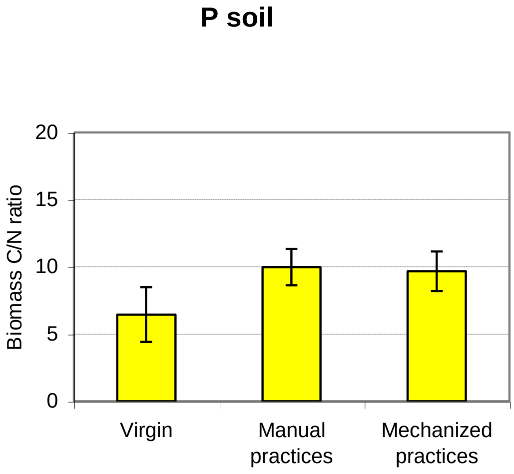
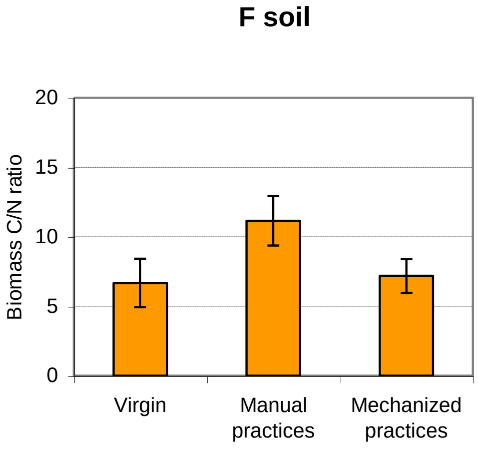
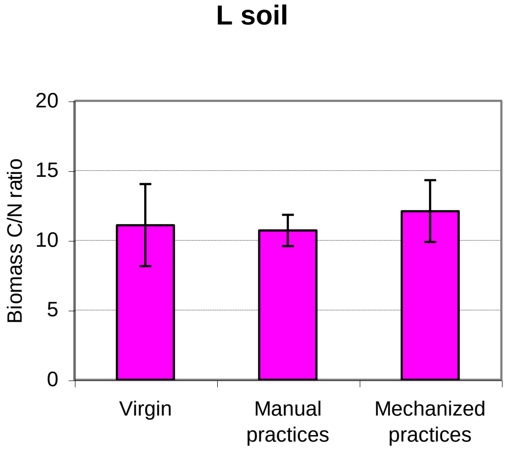


Figure 5.7 Effects of manual and mechanized sugar cane cropping practices on biomass nitrogen content (kg/ha over 15 cm soil depth) of the five major soil groups of Mauritius


B soil


P soil


F soil


L soil

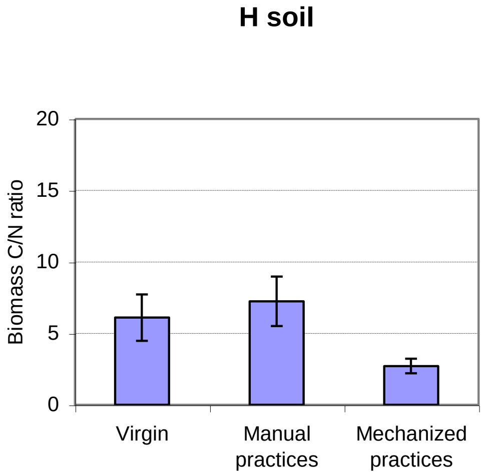

H soil

Figure 5.8 Effects of manual and mechanized sugar cane cropping practices on biomass carbon:nitrogen ratio of top 15 cm of the five major soil groups of Mauritius

Sugar cane cropping either had no effect, or led to a substantial fall in microbial biomass. Thus, the biomass C and N contents of the B and L soils did not change significantly upon conversion to sugar cane cropping, these soils already having low biomass C and N under native vegetation. The biomass C content of the P soil was not significantly affected by cropping, as opposed to its biomass N, which was significantly reduced. A highly significant decrease in microbial biomass occurred with sugar cane cropping in the H and F soils. The biomass C and N contents of the H soil fell to about a third of the values found under native vegetation. In the F soil, biomass N content also fell to a third of its initial value, while biomass C content was almost halved with sugar cane cropping. Sugar cane-cropped soils either had a higher, or an unchanged, biomass C/N ratio compared to soils under native vegetation. The increase in biomass C/N ratio with sugar cane cropping was significant in the P and F soils.

With the adoption of mechanized practices, biomass C content increased significantly in the sub-humid L and P soils, but decreased significantly in the humid H and super-humid F soil, whereas the biomass C content of the rocky B soil was not significantly affected. On the other hand, the adoption of mechanized practices enhanced the microbial biomass N in the P and H soils. In the B, F and L soils, the biomass N increase with mechanization was not significant. Biomass C/N ratio decreased with the adoption of mechanized practices in the rock-free H and F soils. There was no change in biomass C/N ratio in the P, L and B soils.

As carbon in the microbial biomass is energy stored for microbial processes, microbial biomass C content is therefore an indication of potential microbial activity (Rice *et al*., 1996). The decline in biomass C and N observed with sugar cane cropping in the H and F soils was expected in view of the decline in OC concentration in the upper 15 cm of these soils (Figure 5.1). In contrast, there was a much less marked decrease in OC concentration in the top 15 cm of the L and B soils. It was therefore not surprising that the biomass C content was little affected by cultivation in these soils. However, it was not possible to draw any firm conclusion regarding the P soil as its biomass C and biomass N contents were affected differently by cropping. The C/N ratio of micro-organisms is much narrower than that of plant residues, varying usually between 4 and 9 (Brady, 1974) as compared to 128 for cane trash in Mauritius (Ng Kee Kwong *et al*., 1987). Bacterial tissue is generally richer in proteins than fungi and has consequently a narrower C/N ratio. The increased biomass C/N ratio of the sugar cane cultivated P and F soils was an indication that there had been a shift in the composition of the microbial population in these two soils, for instance with a relative increase in the fungal population at the expense of the bacterial one.

The increase in biomass C content in the mechanized fields of the sub-humid soils was probably caused by different factors. There was an increase in the microbial population in the P soil as a result of the large amount of OM introduced after mechanization. On the other hand, there was no such build-up in OM in the L soil and its microbial population might be related to a difference in the nature of the SOM present in its mechanized fields compared to the manually cultivated ones. This was illustrated by the lower C/N ratio of the SOM in the mechanized fields, indicating that the residues were easier to decompose, hence the higher microbial population. In the soils from the humid and super-humid zones, biomass C tended to decrease with the adoption of mechanized practices but the opposite was true for biomass N. This reversal in trend obviously impacted on their biomass C/N ratio. No definite conclusion could therefore be drawn on the effects of adopting mechanized practices on the biomass content of the B, F and H soils. However, the reduced microbial C/N ratio under mechanized conditions in the H and F soils indicated that there was a possible increase in the bacterial population relative to the fungal one.

5.3.2.2 Microbial biomass and length of time during which sugar cane has been cropped manually

The effect of length of time under sugar cane cultivation was to increase the biomass C content in the two sub-humid soils (Figure 5.9). The L soil cultivated for a longer time with sugar cane had a significantly higher value than the recently cultivated soil. On the other hand, the difference between the two treatments was too small to be significant in the P soil. The evolution of biomass N with time under sugar cane cultivation differed for the P and L soils (Figure 5.9). In the rocky P soil, there was more biomass N in the recently cultivated fields and it thereafter declined with time. The rock-free L soil, on the contrary started with a low biomass N, which like biomass C, increased significantly with time under sugar cane cropping, an indication that microbial biomass accumulated with time in this soil. There was no significant effect of time under sugar cane cropping on the biomass C/N ratio of the L soil (Figure 5.9). On the other hand, biomass C/N ratio increased significantly with time in the P soil.

This trend towards higher biomass C and N content with time in the manually cultivated L soil followed a similar trend in higher OC concentration in its topsoil. There was thus a biomass accumulation with time as the microbial population increased in parallel with the rise in SOM. On the other hand, the decline of microbial N with time in the P soil was contrary to the evolution of its biomass C, which remained unaffected, thereby demonstrating that the decline in biomass N occurred through changes in the biomass C/N ratio.

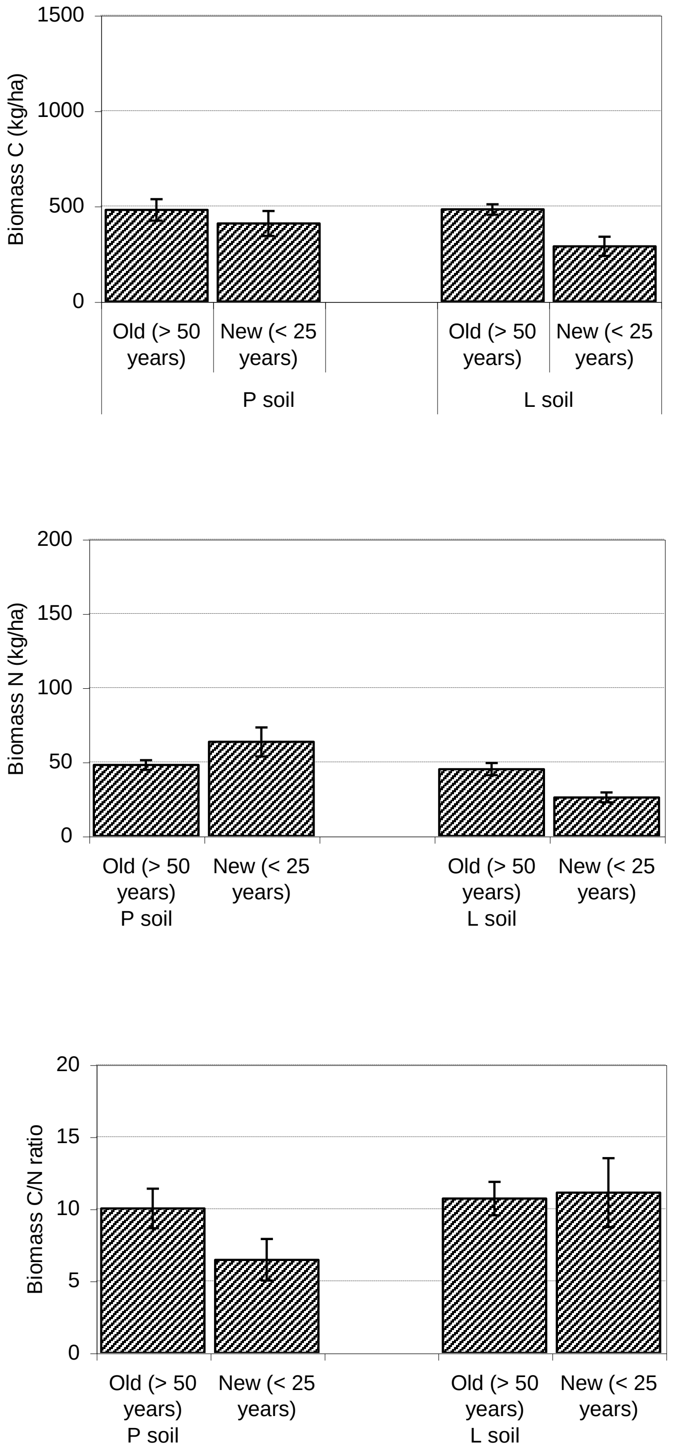


Figure 5.9 Effects of length of time under manual sugar cane cropping on biomass C and N contents (kg/ha over 15 cm soil depth), and biomass carbon:nitrogen ratio of the two major soil groups in the sub-humid zone of Mauritius

5.3.2.3 Microbial biomass and length of time during which mechanized practices have been adopted

The microbial biomass C content of the P soil was higher in the fields recently-mechanized than in those where mechanized practices have been adopted for a longer period (Figure 5.10), but the difference was not significant. Contrary to biomass C, the biomass N content of the P soil increased significantly with time under mechanization (Figure 5.10). Furthermore, the longer mechanized practices have been adopted in the P soil, the lower was its biomass C/N ratio (Figure 5.10). Thus, under long-term mechanization, the ratio decreased significantly to less than half its original value. This change as explained above indicated an evolution in the composition of the microbial population, most probably because the nature of the SOM had changed with time. Under recently mechanized conditions, there was an initial breakdown of the more easily decomposed organic material by a particular group of micro-organisms. In the long term, these subsided as they ran out of food and a different type of micro-organisms would then predominate, having to decompose the remaining, more resistant SOM. The change in C/N ratio of the microbial population would thus reflect this type of microbial evolution.

5.4 Conclusion

The effects of sugar cane cultivation on the biological properties of the major soils of Mauritius were variable, with a clear dependence upon the climatic zone in which these soils occur. This association of biology with climatic zone was related to the cultural practices that predominated in the different zones and which impacted on the return of organic residues to the soil. The practice of burning before harvest in the drier zone compared to green cane harvesting in the wetter zone was probably the one element that had the greatest influence on SOM and the microbial population. Sugar cane cultivation did not necessarily degrade the soil's biological properties. In the dry zone, irrigated agriculture boosted biomass production and enhanced residue return to the soil. It was true that mechanization tended to impact

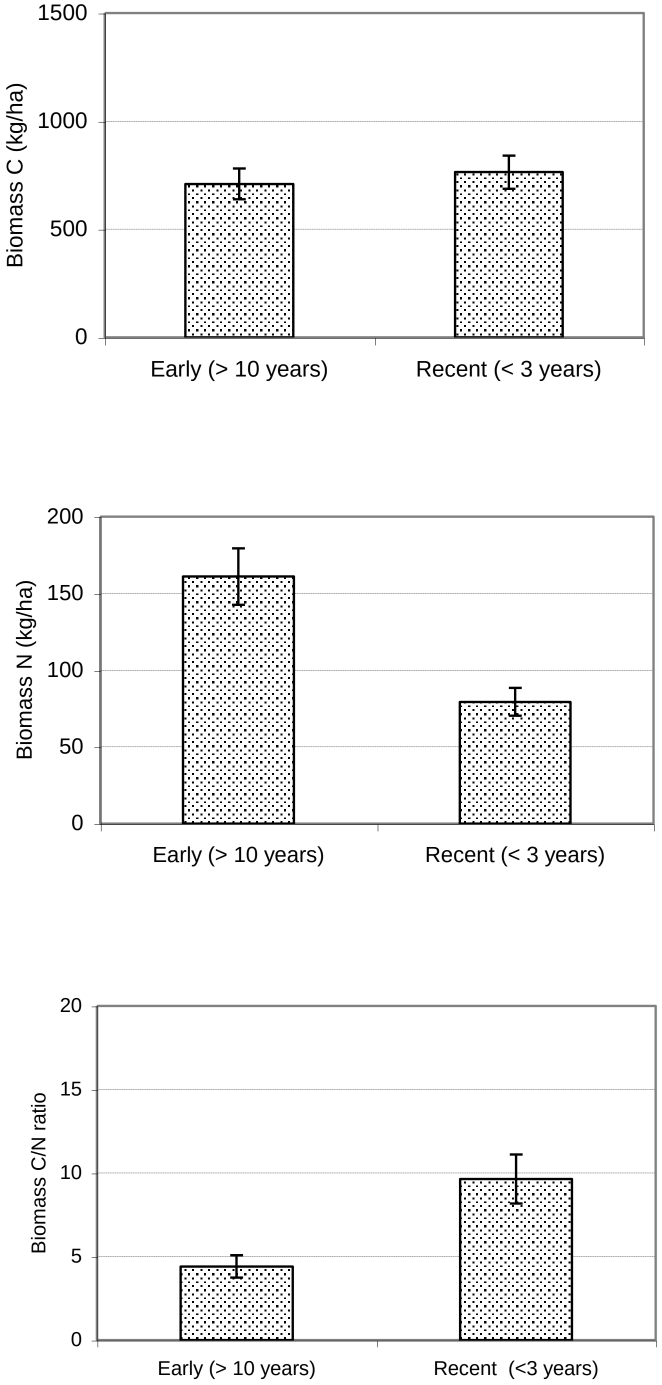


Figure 5.10 Effects of length of time for which mechanized practices have been implemented on biomass C and N contents (kg/ha over 15 cm soil depth) and biomass carbon:nitrogen ratio of P soil of Mauritius cropped with sugar cane

negatively on both SOM and microbial properties, except for the P soil. The latter did not follow the same trend as the other sites since the estate had taken the precaution of alleviating the negative effects of land preparation and rock removal by the addition of large amounts of organic amendments. It was therefore not surprising that the P soil should have had better biological properties after mechanization.

It was difficult to draw clear conclusions regarding the effect of time under sugar cane cultivation on the biological properties of the sub-humid soils. Nevertheless, it can be stated that these properties were not systematically degraded under long-term cultivation in both L and P soils. It was under long-term mechanized practices that the soil biological quality was clearly depressed. This resulted from the practice of applying large amounts of organic amendments to the soil during land preparation and of letting them be used up, so that the soil started with initially high contents of SOM and microbial biomass and ended up with much lower contents in the long-term.

CHAPTER 6

INFLUENCE OF SUGAR CANE PRODUCTION ON SOME SOIL CHEMICAL PARAMETERS

6.1 Introduction

The soil chemical parameter that had been the subject of most studies is pH. In addition to changes in the topsoil and subsoil, measurements were made on its evolution with time and possible causes for its change have been discussed. The other chemical parameters that had been considered to be sufficiently important to warrant study include cation exchange capacity (CEC), levels of plant nutrients such as calcium, magnesium, potassium and phosphorus, and the salinity and sodicity of soils as expressed by their electrical conductivity (EC) and sodium adsorption ratio (SAR).

In general, soils became more acid under sugar cane (Haynes and Hamilton, 1999) and had a higher exchangeable aluminium level (Wong You Cheong and Chan, 1977) than under native vegetation. Topsoil pH was found to decrease immediately after planting of sugar cane by a maximum of 0.8 pH unit, but to rise again in the long term (Masilaca *et al*., 1986). Cropping under sugar cane also leads to a simultaneous drop in pH in the topsoil and a rise in the subsoil, as bases were leached from the topsoil into the subsoil following irrigation (Henry and Ellis, 1996). Acidification in both topsoil and subsoil was also shown to occur (Hartemink, 1998c), while there were also cases where no significant change happened when native soils were put under sugar cane production (Van Antwerpen and Meyer, 1996).

The most frequent finding was that acidification occurred when soils under native vegetation were converted to sugar cane. Schroeder *et al*. (1994) believed that such an acidification was the most important yield-limiting factor in the KwaZulu-Natal region of South Africa, while Noble *et al*. (1997) concluded that a continual decline in soil pH would affect the long-term sustainability of sugar cane production systems. In such a case, corrective measures such as liming were necessary, or else soil acidification would ultimately become a threat to the long-term fertility of the soil and therefore to the sugar industry. The rate of this process could be quite fast, since almost a six-fold increase in hydrogen ion activity was noted over 15 years in one instance (Meyer *et al*., 1998), while the rate of decline of soil pH could range from 0.025 pH unit year^{-1} (Qongqo and Van Antwerpen, 2000) to 0.047 pH unit year^{-1} (Hartemink, 1998c).

Oxidation of ammoniacal fertilizers to nitrate, mineralization of organic matter and leaching of basic cations were identified as the three main causes for acidification of soils under sugar cane (Meyer *et al*., 1998). The most pronounced effect on pH was ascribed to ammonium sulphate fertilizer (Wood, 1965; McLean, 1975; Wood, 1985), which had twice the acidifying power of the most commonly used N fertilizer, i.e. urea (Noble *et al*., 1997). For both forms of fertilizer, nitrification by the soil microbial population was the driving force behind the acidification process (Haynes and Hamilton, 1999). This direct involvement of fertilizers was confirmed by the much lower soil pH values in fertilized treatments compared to unfertilized ones (Graham *et al*., 1999).

CEC was also affected by sugar cane cultivation and its changes tended to reflect changes in SOM content as the latter was a major contributor to exchange sites. In general, sugar cane soils had lower CEC than soils under native vegetation on account of their lower OM contents (Wood, 1985; Henry and Ellis, 1996; Hartemink, 1998b). Nevertheless, the value of topsoil CEC could also remain unaffected by sugar cane cultivation (McLean, 1975), whereas subsoil CEC could increase as a result of downward transfer of OM when the soil was mixed and rotovated during land preparation at planting (Masilaca *et al*., 1986).

The levels of plant nutrients in sugar cane soils were estimated by the balance of fertilizer inputs against crop removal, plus other losses such as leaching (Haynes and Hamilton, 1999). Contents of two important exchangeable bases, namely calcium and magnesium, tended to decrease under sugar cane cultivation (Wood, 1985; Masilaca *et al*., 1986; Van Antwerpen and Meyer, 1996; Meyer *et al*., 1998; Qongqo and Van Antwerpen, 2000) because insufficient amounts of bases had been added to compensate for crop removal and leaching (Masilaca *et al*., 1986). Exchangeable potassium levels followed a similar decreasing trend (Hartemink, 1998b; Henry and Ellis, 1996), even though potassium build-up could also occur in soils under sugar cane as a result of overuse of potassium fertilizers by growers (Meyer *et al*., 1998) or by disposal of stillage slop in the cane fields. The amounts of extractable phosphorus in sugar cane soils also depended on nutrient balance and could therefore either increase (McLean, 1975; Wood, 1985; Henry and Ellis, 1996) or decrease (Van Antwerpen and Meyer, 1996; Meyer *et al*., 1998; Hartemink, 1998a). These changes were mostly confined to the topsoil and very little phosphorus was removed from soil horizons below 30 cm.

Indicators of salinity and/or sodicity, such as EC and SAR, were affected essentially under irrigated conditions and depended on irrigation water quality. For instance, these parameters could be greatly improved if sugar cane was irrigated with good quality water associated with surface and subsurface drainage and the application of gypsum to replace sodium ions with calcium (Henry and Ellis, 1996). However, the opposite could also occur in irrigated sugar cane soils compared to virgin soils if no appropriate corrective measure was taken (Van Antwerpen and Meyer, 1996).

Changes in some chemical properties of the major soils of Mauritius, as a result of sugar cane cropping, are reported in this chapter. Four indicators of chemical quality, namely pH, CEC, exchangeable bases and base saturation, were assessed following manual sugar cane cropping on all five major soil groups. On the same soil groups, the effects of adopting mechanized practices were also measured. In addition, the effects of time under manual and mechanized sugar cane cropping practices for selected soil groups are also dealt with.

6.2 Procedure

6.2.1. General

Chemical quality parameters that have been studied in the major soil groups of Mauritius were pH, cation exchange capacity, exchangeable bases (Ca, Mg, K and Na) and base saturation. A complete description of the methodology used to measure pH, CEC and concentration of individual bases is given in Chapter 4.

All measurements have been made in the laboratory on the soil fraction of the samples, as defined in Section 5.2.1. The concentration of the four individual exchangeable bases was determined on air-dried soil samples in the laboratory and expressed in g kg^{-1}. These values were then converted to $cmol_c$ kg^{-1}, the same unit as for CEC, by using a conversion factor derived from the relative atomic mass of each element and their valency (Table 6.1).

Table 6.1 Weight in gram of one $cmol_c$ kg^{-1} of exchangeable chemical elements (adapted from Baize, 1993)

Exchangeable chemical	Weight (g)
1 $cmol_c$ kg^{-1} of K^+	0.03910
1 $cmol_c$ kg^{-1} of Ca^{2+}	0.02005
1 $cmol_c$ kg^{-1} of Mg^{2+}	0.01215
1 $cmol_c$ kg^{-1} of Na^+	0.02300

Since the concentration of individual bases and the CEC were both in $cmol_c$ kg^{-1}, these parameters were used directly to derive the base saturation (BS) of the soil samples in percentage using Equation 6.1.

$$BS = 100 \times \{[Ca] + [Mg] + [K] + [Na]\} / CEC \qquad (6.1)$$

6.2.2 Data processing and analysis

The same procedure as described in Section 5.2.2 has been adopted to calculate the average value of the measurements and their standard error, giving a single representative point per parameter while encompassing all the variability of the result.

6.2.3 Data presentation

A similar procedure as described in Section 5.2.3 has been used to present the data sets, namely the average values and their standard errors were plotted on graphs. For each chemical parameter the soil depth was on the y-axis while the parameter concerned was on the x-axis. Again, the data for each soil layer were represented in one single point in the middle of the layer concerned. The evolution of every parameter with depth for each treatment was thus expressed in the form of a line graph, and horizontal error bars showed the standard error for each data point.

6.3 Results and discussion

6.3.1 Soil pH

6.3.1.1 Effects of manual and mechanized sugar cane cropping practices on soil pH

Under native vegetation, the sub-humid P and L soils were close to neutral, with pH values of 7.0 for the P soil and 6.3 for the L soil (Figure 6.1). The lower pH of the L soil compared to the P soil was related to the longer period during which the former had been subjected to leaching, since it was derived from older parent material. The humid H soil and the super-humid F soil were acidic, in the pH range of 5.0, as expected for soils whose formation had

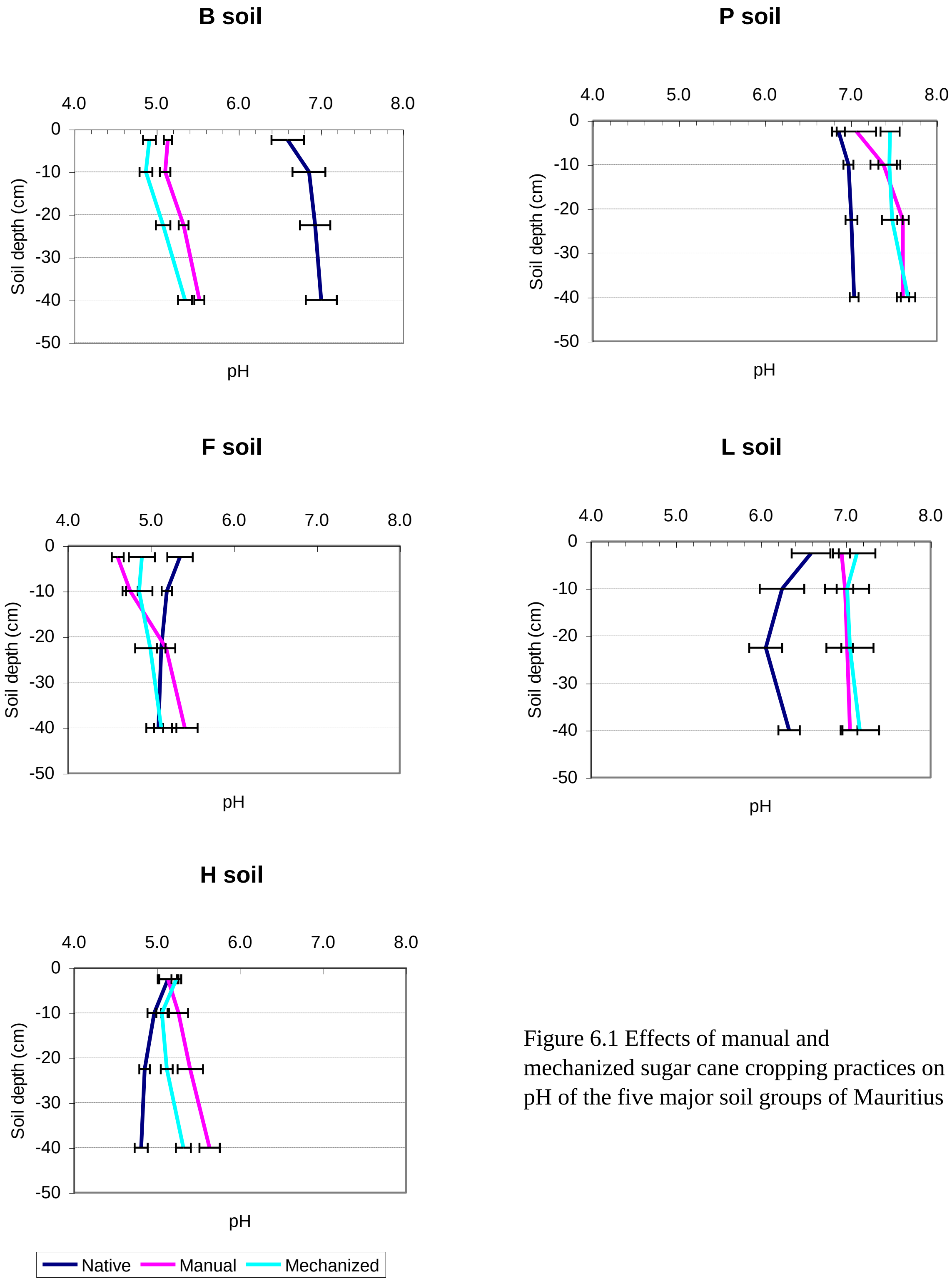


Figure 6.1 Effects of manual and mechanized sugar cane cropping practices on pH of the five major soil groups of Mauritius

occurred under conditions of heavy rainfall with most bases having been leached out of the profile. However, the other soil from the super-humid zone, the rocky B soil, was surprisingly close to neutrality, whereas it should at best have been slightly acidic (Parish and Feillafé, 1965). In terms of individual soil layers, pH tended to increase slightly with depth in the rocky P and B soils, but to decrease in the rock-free L, H and F soils.

The abnormally high pH of the B soil under native vegetation shows that the site had not been under virgin conditions at sampling time. Since soils from this group normally have a pH varying between 5.0 and 6.3, with an average value of 5.5 (Parish and Feillafé, 1965), the measured values of 6.6 to 7.0 indicate that some form of amendment had been made to the site. This zone was under a vegetation of grass and coniferous trees and had obviously not been cultivated for a long time. However, this does not preclude the possibility that it could have received chemical amendments and in view of the high pH, it is probable that some liming agent had been applied. The site was definitely not under virgin conditions in chemical terms, and it would be unwise to compare this soil with the sugar cane cultivated soil. This means that no conclusion should be drawn on the effect of sugar cane cultivation on the pH of the B soil.

Excluding the B soil, sugar cane cropping had variable effects on soil pH. In the sub-humid L and P and humid H soils, cultivation was generally beneficial as it led to higher pH, the increase being significant in most of the profile of the three soils. On the other hand, the pH of the super-humid F soil decreased with sugar cane cropping in the topsoil, but increased in the subsoil.

Changes in soil pH with the adoption of mechanized practices were not as marked as those resulting from sugar cane cropping. There is very little effect in the L and P soils, but the pH of the H soil decreased significantly with mechanization in most of the profile. In the super-humid soils, the effects differed according to rock content. The pH dropped significantly by some 0.2 units in the whole profile in the rocky B soil, but increased in the topsoil of the rock-free F soil.

The higher pH in the L, P and H soils with sugar cane cropping goes against the established pattern noted in most other sugar cane producing countries. It is well established in the literature that acidification followed sugar cane cultivation but in the case of these three soils, this expected acidification did not take place in spite of using fertilizer N. For the H soil, the reason appeared simple enough. It has been common practice to apply liming agents to raise soil pH in the acidic soils in the humid and super-humid zones. Historically, lime was applied at planting at the rate of 150 to 500 kg per arpent, equivalent to 0.36 to 1.2 t ha^{-1}, in the early 1900's (North-Coombes, 1993). MSIRI (1990) recommended that soils under sugar cane should be limed if their pH was well below 5.0, the dose for raising pH by one unit amounting to 8.5, 4.8 and 2.4 t ha^{-1} of coral sand, lime and cement respectively. In the case of the H soil at Beau Champ, the pH of the virgin soil was effectively less than 5 and lime and sand were regularly applied to the sugar cane fields at planting at the recommended rates. As far as the L soil was concerned, there was still evidence of the presence of coral sand in the Richeterre soil samples, mainly small white pieces of coral debris. Sanding had been systematically practiced in areas such as Richeterre in the 1930's, with normal rates of 1 to 5 t per arpent, equivalent to 2.4 to 12 t ha^{-1} (North-Coombes, 1993), and heavier applications had even been made in some instances, up to 15 t per arpent, equivalent to 36 t ha^{-1}. The situation is different for the P soil, where no evidence of sanding had been uncovered. In this case, the pH increase was caused by the practice at Médine of supplementing its mineral fertilizers at planting with 5 t ha^{-1} of composted filter mud and poultry litter. The application of filter mud is a common practice on all estates as it contains about 1% by weight of phosphate (Paturau, 1989), but it is not normally composted. This organic material raises soil pH as it contains some 1% CaO by weight. Poultry litter has a similar pH-enhancing effect in the long-term (MSIRI, 2006). The combined effect of these two organic amendments has probably raised the pH of the P soil, particularly as composted filter mud has again been added in the two subsequent ratoons.

The acidification with sugar cane cropping in the topsoil of the super-humid F soil was probably due to the acidifying effect of ammoniacal fertilizers as noted by Wood (1965), McLean (1975) and Wood (1985). These fertilizers have been applied on a seasonal basis, at the bottom of the furrow in plant cane and at the soil surface in the subsequent ratoons. If they had any acidifying effect, it should have been felt close to the soil surface and acidification therefore occurred mainly within the topsoil. In this case the addition of 25 t ha^{-1} of filter mud in the cane furrow at planting was not sufficient to counteract the acidifying effects of the fertilizers. Further acidification of the topsoil could have occurred through leaching of basic cations as described by Meyer *et al*. (1998). This leaching process could also explain why pH tended to increase in the F subsoil.

The adoption of mechanized practices ought to have had little effect on chemical properties, since the practices that affect the latter, such as fertilization, application of organic manure and pH-enhancing amendments, were not modified with mechanization. This was what effectively happened with the pH of the sub-humid L and P soils, which remained essentially unaffected by mechanized practices. However, there was an acidifying trend with mechanization in the humid H soil and the super-humid F and B soils, which could be correlated with the lower calcium content of these soils under mechanized conditions (Figure 6.8). This acidification was probably an artifact rather than a consequence of mechanization.

6.3.1.2 Soil pH and length of time during which sugar cane has been cropped manually

There was a slight, but insignificant, acidification with time under sugar cane cropping in the rock-free L soil (Figure 6.2), showing that a balance in pH had been struck early on when the virgin L soil was put under sugar cane cultivation. Conversely, there was a significant pH drop with time in the topsoil of the rocky P soil, accompanied by a small rise in the subsoil.

The process driving this pH change was probably the same as that described by Henry and Ellis (1996), whereby acidification of the topsoil with time was caused by leaching of bases down the profile because of irrigation, with surface banding of fertilizers in ratoons as a possible additional cause.

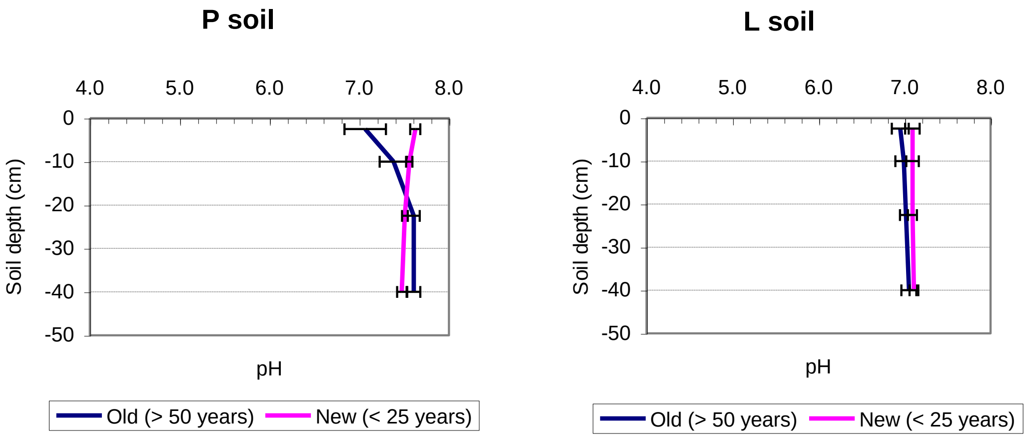


Figure 6.2 Effects of length of time under manual sugar cane cropping on pH of the two major soil groups in the sub-humid zone of Mauritius

6.3.1.3 Soil pH and length of time during which mechanized practices have been adopted

The pH of the P soil tended to be higher when mechanized practices had been adopted for a longer period (Figure 6.3), but the difference was not significant. It thus appears that the soil pH had reached an equilibrium value very rapidly following the introduction of mechanized practices.

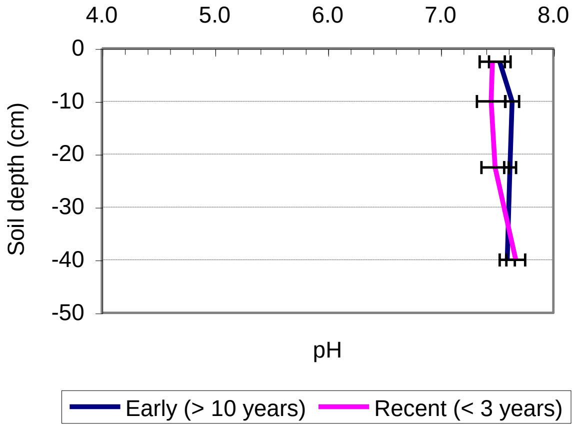


Figure 6.3 Effects of length of time for which mechanized practices have been implemented on pH of P soil of Mauritius cropped with sugar cane

6.3.2 Cation exchange capacity

6.3.2.1 Effects of manual and mechanized sugar cane cropping practices on cation exchange capacity

Under native vegetation, the rocky P and B soils had a comparatively higher CEC than the rock-free L, H and F soils. The CEC value of these first two soils was in the order of 30 $\mathrm{cmol_c\ kg^{-1}}$ in the topsoil and 26 $\mathrm{cmol_c\ kg^{-1}}$ in the subsoil (Figure 6.4). The lowest values were found in the rock-free L and F soils, where they decreased with depth from 20 $\mathrm{cmol_c\ kg^{-1}}$ to 12 $\mathrm{cmol_c\ kg^{-1}}$. The humid H soil had intermediate CEC values, with 25 $\mathrm{cmol_c\ kg^{-1}}$ in the topsoil and 18 $\mathrm{cmol_c\ kg^{-1}}$ in the subsoil. For all soil groups, CEC decreased with depth, showing that organic matter content was a major source of this property.

In most cases, CEC values tended to be higher with sugar cane cropping compared to native vegetation, with the H topsoil as the only exception. The rise in CEC was not systematically significant in the other soils and there was indeed no significant effect of cropping in the rocky P and B soils. The effects were also not significant in the topsoil of the rock-free L and F soils.

With the adoption of mechanized practices, the changes in CEC were variable and were related to climatic zone. Thus, the sub-humid L and P soils had an unchanged or increased CEC depending on soil depth, while the humid H soil and super-humid F and B soils had significantly lower CEC throughout the profile. The increase was quite substantial in the subsoil of the P soil, but was less pronounced in the L soil.

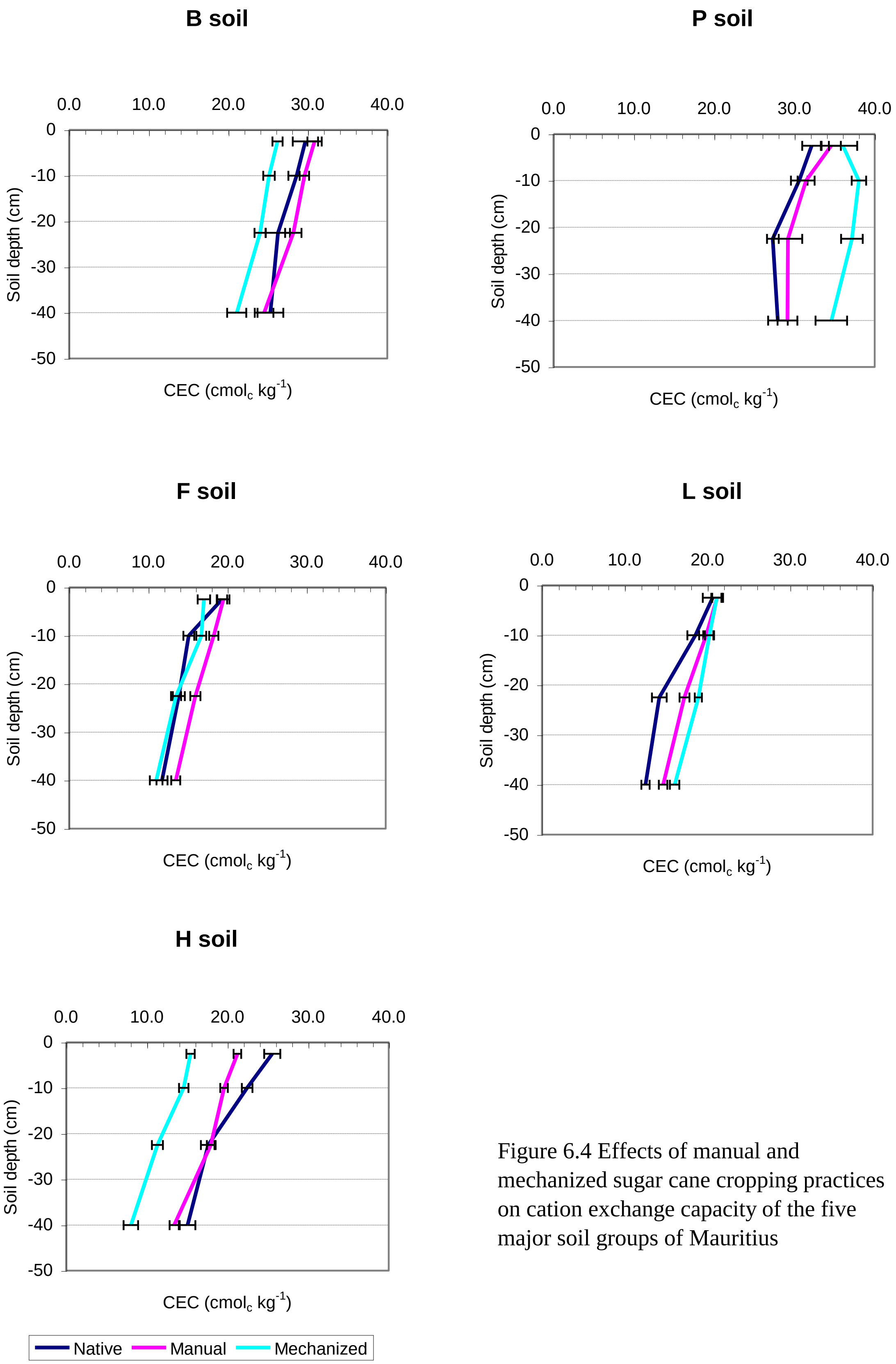


Figure 6.4 Effects of manual and mechanized sugar cane cropping practices on cation exchange capacity of the five major soil groups of Mauritius

CEC depends essentially upon organic matter content and soil texture, particularly the amount and the kind of clay present (Brady, 1974). The significant CEC increase noted with cropping in the L and F subsoil and the drop in the H topsoil could not be ascribed to textural changes as mechanical analysis had not shown any significant change in their clay content (Figure 7.2). It is most likely that these changes were related to changes in SOM content as the OC concentration of the H topsoil fell from 5.9 to 3.4% while that of the L and F subsoil increased by some 0.3 and 0.5% respectively (Figure 5.1).

The adoption of mechanized practices led to lower CEC values under humid and super-humid conditions and higher ones under sub-humid conditions. It is difficult to relate this observation to a precise cause since SOM content did not systematically decline with mechanization in the humid and super-humid regions, nor did it significantly increase in the sub-humid region. In such instances, it would appear that the changes were caused by a combination of the various factors that influence CEC, namely SOM and nature and amount of clay, as well as the effect of pH increase in the sub-humid soils, given that CEC tends to increase with soil pH in most soils (Brady, 1974).

6.3.2.2 Cation exchange capacity and length of time during which sugar cane has been cropped manually

The longer the rocky P soil had been cropped with sugar cane, the higher the CEC rose (Figure 6.5). However, the opposite trend was found in the rock-free L soil, where length of time under cropping led to lower CEC values in the subsoil.

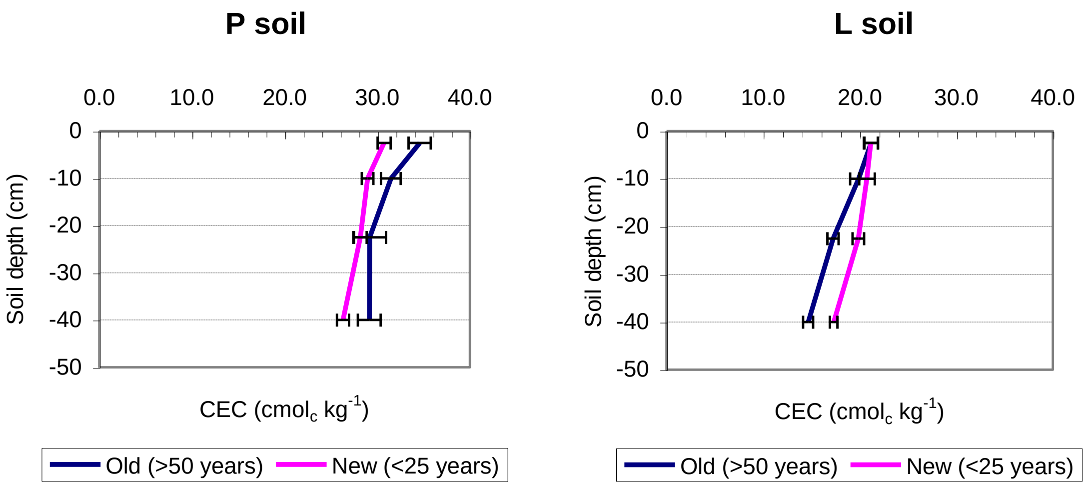


Figure 6.5 Effects of length of time under manual sugar cane cropping on cation exchange capacity of the two major soil groups in the sub-humid zone of Mauritius

The increase in CEC with time in the P soil was again linked to OM, since its OC content increased significantly with time (Figure 5.4). In the L soil, OC content did not change with time, so that the lower CEC values in the subsoil could not be directly attributed to a lower OM content. The exact cause for this observation could not be ascertained, but was probably the result of a combination of factors, namely SOM, nature and amount of clay, and pH as discussed previously.

6.3.2.3 Cation exchange capacity and length of time during which mechanized practices have been adopted

The fields that have been mechanized during a long period had a much lower CEC than those that have only recently been mechanized (Figure 6.6). This significant CEC decrease with time was observed throughout the whole soil profile and could be directly attributed to the significant fall in OM content with time in the mechanized fields (Figure 5.5).

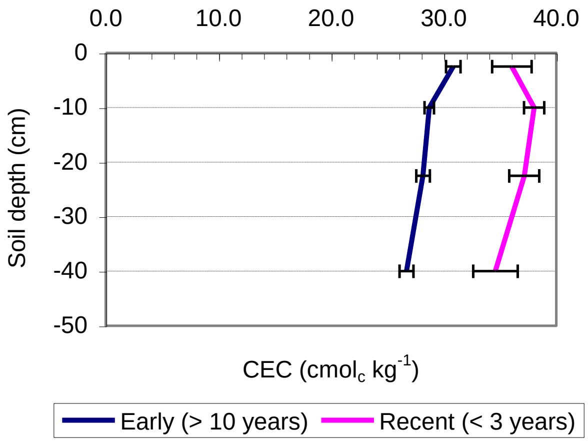


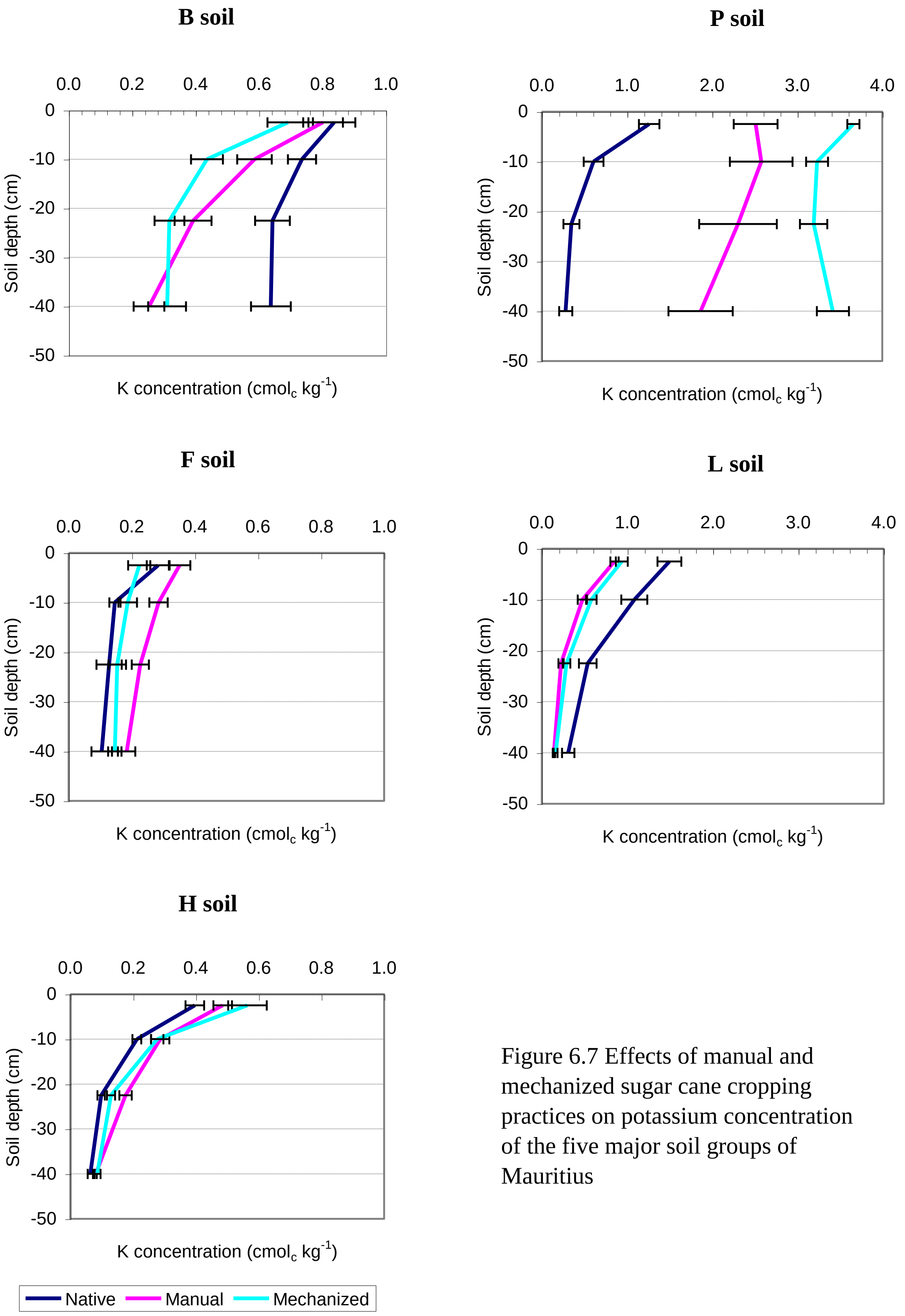
Figure 6.6 Effects of length of time for which mechanized practices have been implemented on cation exchange capacity of P soil of Mauritius cropped with sugar cane

6.3.3 Exchangeable bases

6.3.3.1 Effects of manual and mechanized sugar cane cropping practices on exchangeable bases

Of the four exchangeable bases under study, Na is of little agronomic importance, even though it plays a major part wherever there are salinity problems. As there were no salinity problems in the soils of Mauritius, only K, Ca and Mg have been discussed.

Under native vegetation, the sub-humid L and P soils contained more exchangeable bases than the wetter H and F soils (Figures 6.7, 6.8 and 6.9). This trend was expected as soils were subjected to greater leaching in the wet zones and thus to higher losses of bases. However, the B soil went against this trend as it had a high Ca content, an anomaly that also explained its unexpectedly high pH. The exchangeable base values of the virgin B soil should therefore not be considered as they were unreliable.


B soil

P soil

F soil

L soil

H soil

Figure 6.7 Effects of manual and mechanized sugar cane cropping practices on potassium concentration of the five major soil groups of Mauritius

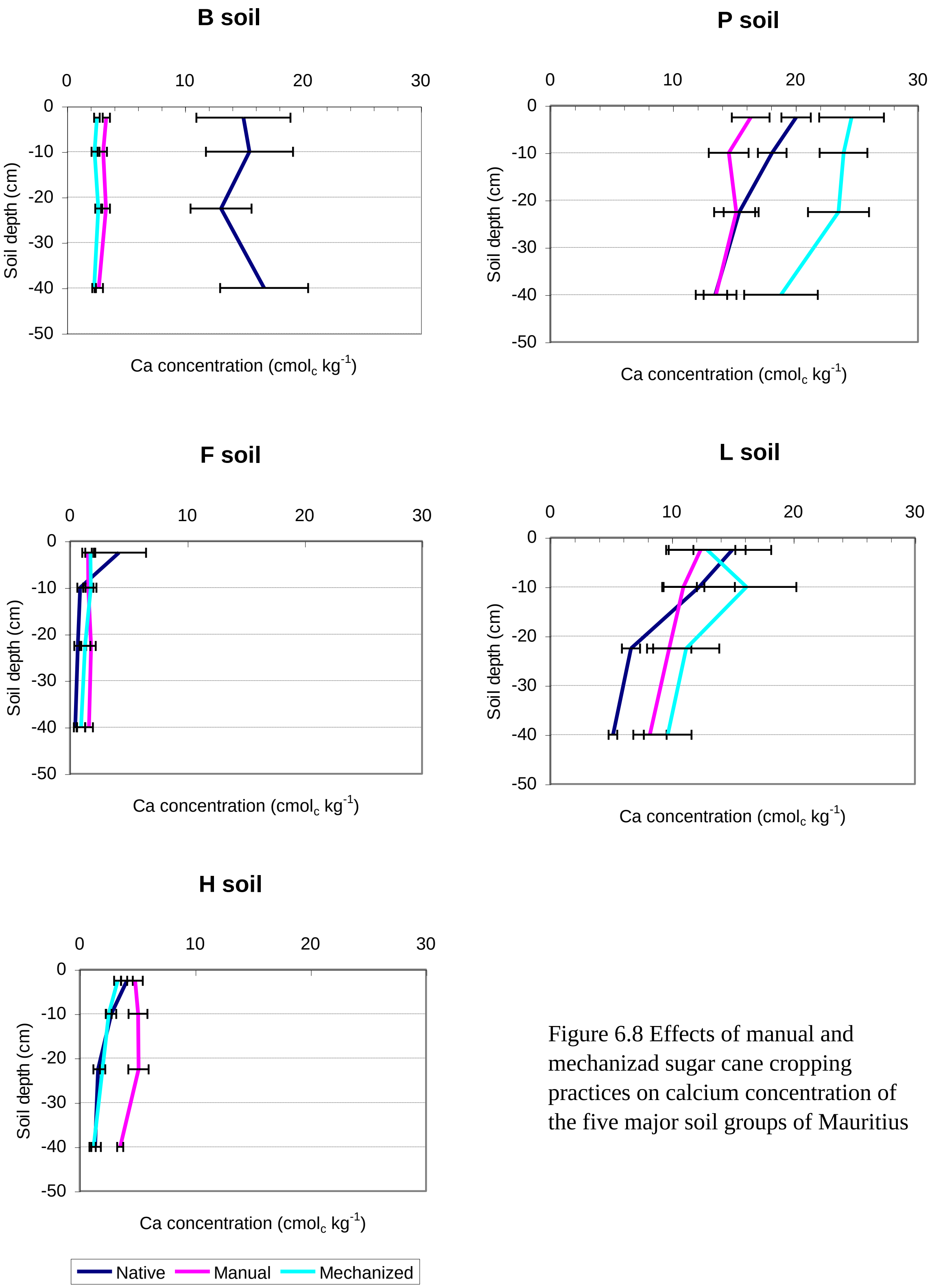


Figure 6.8 Effects of manual and mechanizad sugar cane cropping practices on calcium concentration of the five major soil groups of Mauritius

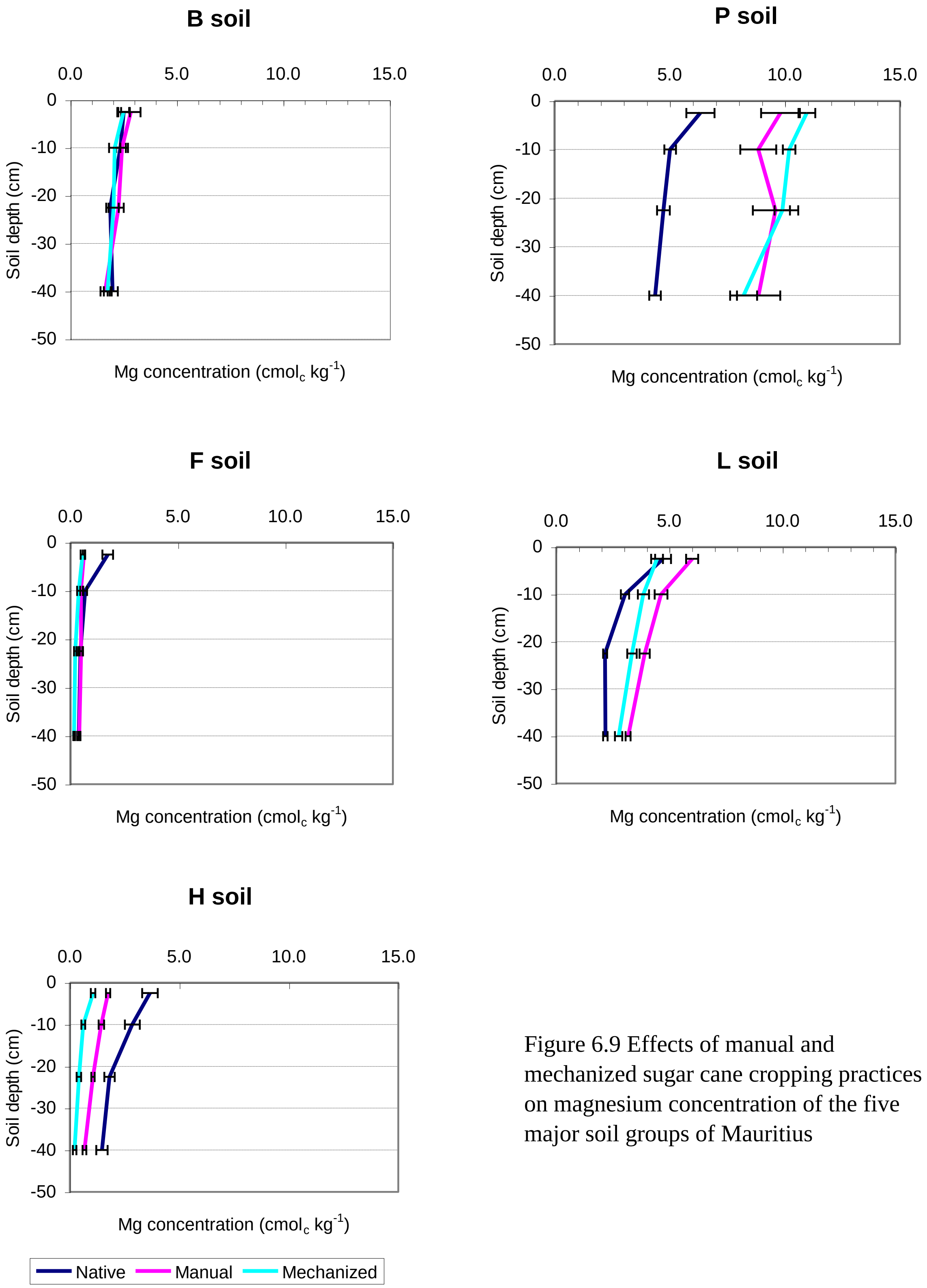


Figure 6.9 Effects of manual and mechanized sugar cane cropping practices on magnesium concentration of the five major soil groups of Mauritius

In general, sugar cane cropping did not have negative effects on exchangeable bases. Potassium, the most important base in agronomic terms, increased significantly with cropping in the P, F and H soils (Figure 6.7). The L soil was the only one where K concentration decreased with cropping. Calcium decreased in the topsoil of the L, P and F soils, but increased in the subsoil of the L and F soils and in the whole profile of the H soil (Figure 6.8). Magnesium increased in the sub-humid L and P soils, but decreased in the H and F soils (Figure 6.9).

The adoption of mechanized practices also did not depress the exchangeable base status in all the soils. In fact, K, Ca and Mg concentration increased in the P soil, but Mg concentration generally decreased with the adoption of mechanized practices in the other soils. The F and H soils were the only ones to experience a fall in K and Ca concentration respectively.

The sugar cane crop requires large amounts of K (Clements, 1980). The exact amount of nutrient extracted is not constant and depends on soil type, climate and fertilization method. Thus, in India, a crop of 125 t ha^{-1} removed some 130 kg K ha^{-1} (Yadav and Prasad, 1992) whereas 1.33 to 1.97 kg K were extracted by 1 t stalk in Mexico, (Naranjo de la F. *et al*., 2006) and 2.0 kg K was taken up per t of millable cane in Mauritius (MSIRI, 2005). The natural K fertility of the soils of Mauritius is low and economic crop production requires an input of K fertilizers. Based on the results of soil analysis, K fertilizer is recommended in order to meet plant demand. K fertilization was therefore the probable cause for K increase in the P, F and H soils. The high K value of the P soil is attributable to the practice of the sugar estate, which supplemented its mineral fertilizers with filter mud and poultry litter in manually harvested fields. Filter mud contained 0.017% K on a fresh weight basis (Paturau, 1989) while fresh poultry litter contained some 19 kg K per t (Zublena *et al*., 1996).

It is a recommended practice under sugar cane cropping in Mauritius to add products containing Ca to correct pH should the latter be lower than 5.0. In highly leached regions, calcium silicate is also recommended to correct for silicon deficiency, since silicon has a beneficial effect on sugar cane yield (Wong You Cheong, 1970). Further sources of Ca include fertilizers, such as calcium ammonium nitrate, a source of N, and tricalcium phosphate, used for phosphorus fertilization (Wong You Cheong, 1969), and filter mud. Overall, relatively high amounts of Ca are applied regularly to the fields. It is therefore not surprising that Ca contents should increase or at least stay at similar levels under sugar cane cropping, particularly in super-humid soils. Even in sub-humid soils, where there was a lesser need for Ca compounds, there was no significant net loss, a clear sign that its removal by the sugar cane crop or by leaching had been adequately compensated for.

Unlike Ca, Mg is not added intentionally to the soil through fertilizers or amendments, but is found in some of the organic material that is applied. The most common source is filter mud, where it is present in the range of 0.3 to 0.9% Mg (Paturau, 1989). This filter mud is added to the fields at planting at rates varying between 12 and 28 t ha^{-1}. Where Mg levels increased with sugar cane cropping, as in the L, P and B soils, it is most likely that Mg additions via filter mud were higher than its removal by the crop and losses by leaching. The increase in Mg was more pronounced in the P soil. This was due to the addition of poultry manure and litter to manually-harvested fields at rates of 5 t ha^{-1} in the P soil. As there were about 4 kg Mg t^{-1} of fresh broiler house litter (Zublena *et al.*, 1996), this additional source further contributed to the Mg pool of the P soil. The absence of significant effect with cultivation in the F soil shows that additions were sufficient to balance losses, whereas the significant drop in the H soil means that the Mg added in the filter mud was not sufficient to offset removal by crops and leaching losses.

No change in K content was expected with the adoption of mechanized practices, since the same soil testing principle as for the manual treatment had been applied. This was true for the H, L and B soils, which had similar K contents in both manual and mechanized situations. The much lower K concentration in the F topsoil clearly indicates that K removal by the crop and leaching had not been adequately compensated for by fertilization. This difference could not therefore be attributed to mechanization *per se*. The much higher K content of the P soil under mechanized condition was probably due to rock-crushing and the application of filter mud and stillage slop by the estate upon land preparation. The *in situ* basalt dust produced with rock crushing contains about 0.57% K (D'Hotman de Villiers, 1947), while filter mud and stillage slop contain on average 0.017% K (Paturau, 1989) and 6.5 g K l^{-1} (Booth and Lightfoot, 1990) respectively. The major source of K in this case was most probably the stillage slop, applied at rates of 20 t ha^{-1} at planting.

The significant increase in Ca with the adoption of mechanized practices in the P soil had the same likely causes as for the increase in K. The stillage slop which had been added contained on average 3.8 g Ca l^{-1} (Booth and Lightfoot, 1990), while filter mud contained between 0.6 and 0.8% Ca (Paturau, 1989). A further source of Ca lies in the rock dust that was produced by crushing the stones *in situ*. Basalt dust of this type has been shown to contain some 6.6% Ca (D'Hotman de Villiers, 1947). These practices were not commonplace on other sugar estates, except the routine application of fresh filter mud at planting, and consequently the other soils studied did not show such an increase in Ca concentration.

As with K and Ca, Mg levels increased significantly with the adoption of mechanized practices in the P soil. Large amounts of this exchangeable base had been applied to the soil during land preparation through stillage slop, containing on average 4.3 g Mg l^{-1} (Booth and Lightfoot, 1990), and composted filter mud. There was a further addition of Mg from the doleritic basalt dust produced by stone crushing, with some 6.9% Mg in the dust (D'Hotman de Villiers, 1947). Since there was no similar addition of Mg-containing material in the other soils, except through filter mud, the L, H, F and B soils had much less Mg than the P soil with the adoption of mechanized practices.

6.3.3.2 Exchangeable bases and length of time during which sugar cane has been cropped manually

The exchangeable base concentration of the L soil was not affected by the duration under which it had been under sugar cane cultivation (Figure 6.10). It therefore appears that removal of exchangeable bases by the plant or by leaching had been compensated for adequately in the L soil by addition of fertilizers and filter mud. On the other hand, the K and Mg concentration of the P soil increased with time, while its Ca concentration was not significantly affected. The initial K concentration in the virgin P topsoil was about 1.3 cmol_c kg^{-1}, it increased to 1.5 cmol_c kg^{-1} when the soil was initially cropped with sugar cane and it finally reached a value of 2.5 cmol_c kg^{-1} in the soil cultivated for a long period with sugar cane. This upward tendency is a clear sign that there had been a slow build-up of K with time. This build-up in the P soil was probably the result of an excessive application of K in organic amendments. The same explanation is applicable to the increase with time of the Mg concentration.

6.3.3.3 Exchangeable bases and length of time during which mechanized practices have been adopted

The concentration of exchangeable bases in the P soil was lower in the fields where mechanized practices had been adopted for a long period than those with more recent mechanized practices (Figure 6.11). There had been an initial flush of K, Ca and Mg when the land was prepared for mechanization since substantial amounts of stillage slop and composted filter mud were applied to the soil, coupled with *in situ* rock crushing. Afterwards, the amount of bases declined as they were exported by the crop and lost by leaching, with little further addition to counter-balance these losses.

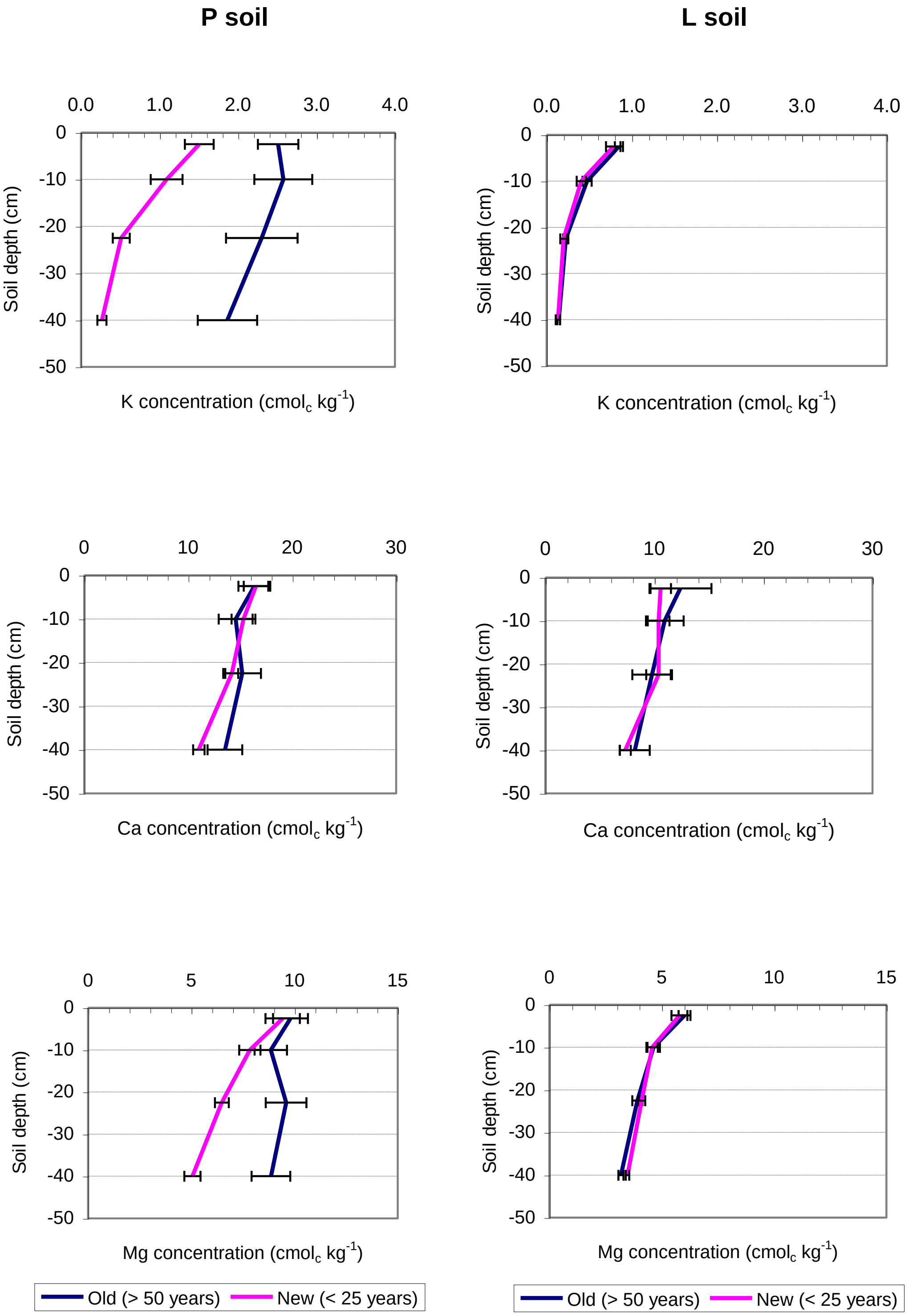


Figure 6.10 Effects of length of time under manual sugar cane cropping on potassium, calcium and magnesium concentrations of the two major soil groups in the sub-humid zone of Mauritius

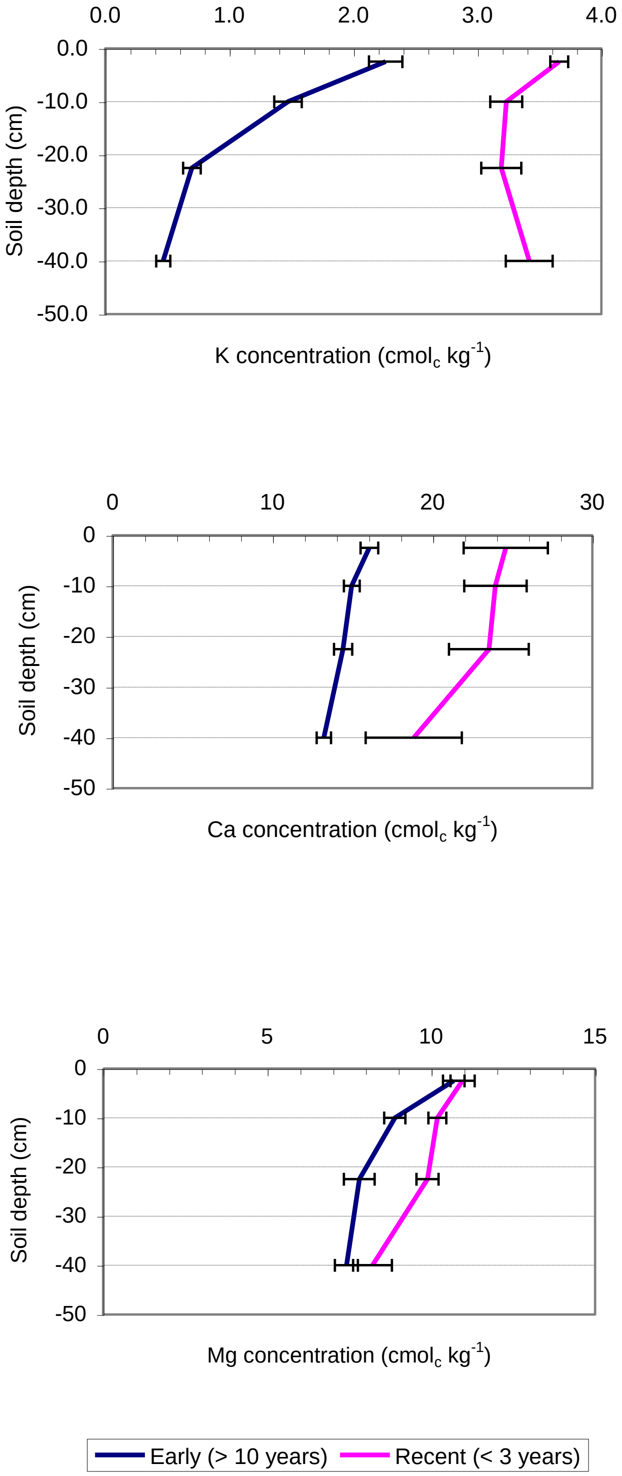


Figure 6.11 Effects of length of time for which mechanized practices have been implemented on potassium, calcium and magnesium concentrations of P soil of Mauritius cropped with sugar cane

6.3.4 Base saturation

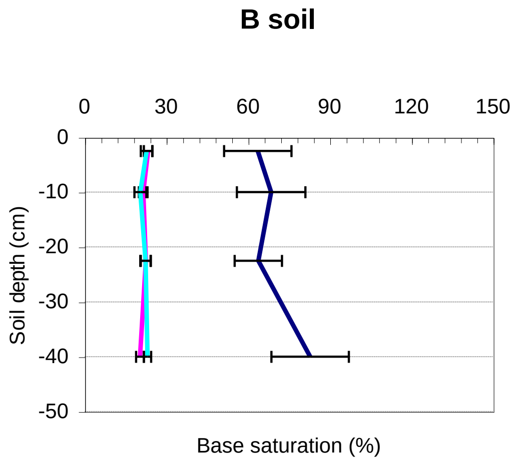
6.3.4.1 Effects of manual and mechanized sugar cane cropping practices on base saturation

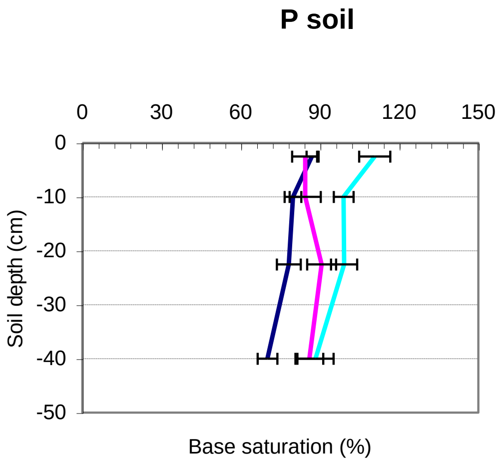
The base saturation of the soils under native vegetation mirrors what has been described for the exchangeable bases: a high value for the sub-humid L and P soils and a low value for the humid H and super-humid F soils (Figure 6.12), but not in the B soil. As discussed with respect to soil pH, data for the B soil under native vegetation were not reliable and could not be compared with the cropped situation.

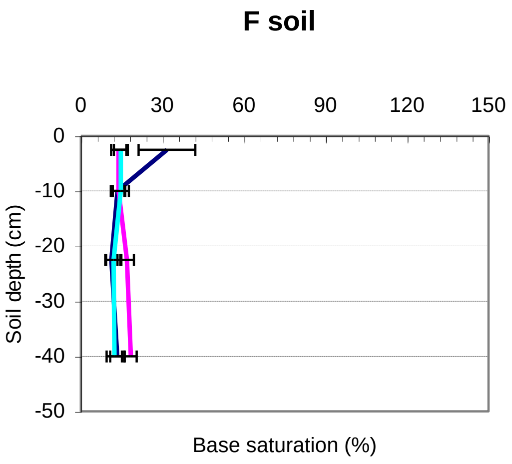
With the exception of the B soil, the base saturation generally increased with sugar cane cropping, but the rise was more noticeable in the subsoil. Thus, significant improvements in base saturation occurred in the L, P, H and F subsoil. There was generally no significant change in the topsoil.

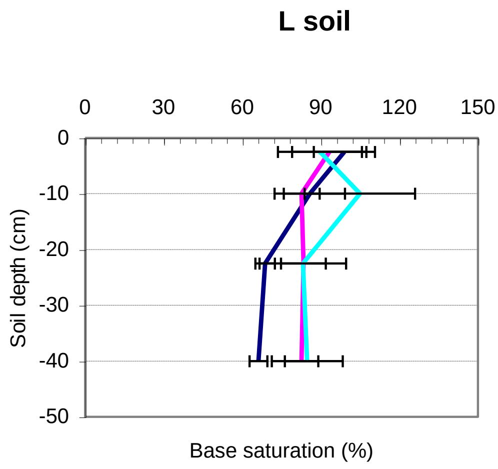
The base saturation changes caused by the adoption of mechanized practices did not seem to be related to rock content or climatic zone. There was very little change in the rock-free L and F soils, but the H soil was affected by mechanized practices as its base saturation fell in the subsoil. Positive effects occurred with mechanized practices in the P soil, where there was a significantly higher base saturation value in the topsoil.

The higher base saturation associated with cropping in the subsoil of the L, P, H and F soils is a clear indication that the addition of bases through fertilizers and other forms of amendments has improved the conditions compared to the soil’s original status. Furthermore, since the amendments and fertilizers were most often applied to the soil surface, the accumulation of bases in the subsoil indicates that there has been a migration of these elements down the profile. The probable causes for such a downward movement were leaching with percolation and mixing through soil tillage. The lack of significant change in base saturation within the


B soil


P soil


F soil


L soil

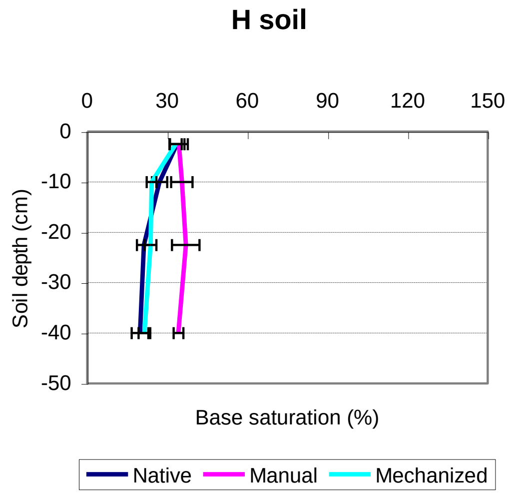

H soil

Figure 6.12 Effects of manual and mechanized sugar cane cropping practices on base saturation (%) of the five major soil groups of Mauritius topsoil indicates that, in this zone, the removal of bases by the crop has been effectively counter-balanced by additions.

The adoption of mechanized practices has had little effect on base saturation. The positive effects noted in the P topsoil were again associated with the heavy organic amendment under mechanized conditions at the sugar estate, especially the addition of large amounts of filter mud and stillage slop, and the practice of stone crushing.

6.3.4.2 Base saturation and length of time during which sugar cane has been cropped manually

The base saturation values were quite high in the sub-humid L and P soils, approaching 100% in some soil layers (Figure 6.13). There has been no significant change in base saturation brought about by the length of time under cropping in the two topsoils. However, base saturation increased significantly with time in the two subsoils.

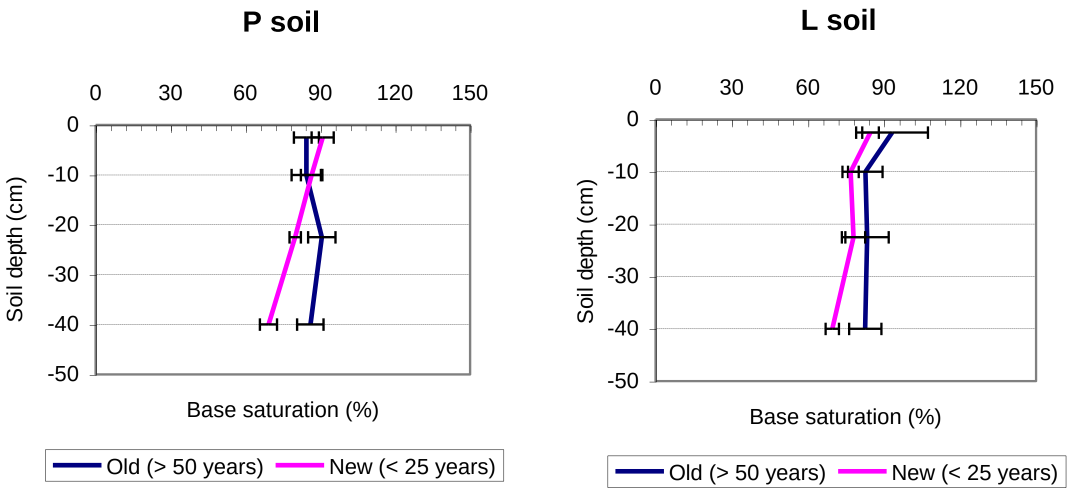


Figure 6.13 Effects of length of time under manual sugar cane cropping on base saturation (%) of the two major soil groups in the sub-humid zone of Mauritius

In spite of the general increase in CEC with time in the P soil, its base saturation still increased in the subsoil. This was essentially due to the high increase in K, and to a lesser extent in Ca and Mg. There was thus an accumulation of bases with time in the subsoil that exceeded the parallel increase in CEC. As far as the L soil is concerned, CEC decreased with time only in the subsoil. In addition, its Ca, Mg and K concentration did not change with time in the whole profile. The net result was that its base saturation increased in the profile but the increase was significant only in the subsoil.

6.3.4.3 Base saturation and length of time during which mechanized practices have been adopted

Irrespective of the length of time under mechanized practices, the base saturation was high, even exceeding 100% in the topsoil of the recently-mechanized fields (Figure 6.14). As opposed to what was found with respect to time under cropping, the base saturation of the P soil decreased with time under mechanized conditions, the change being significant in the whole profile except the lower part of the subsoil.

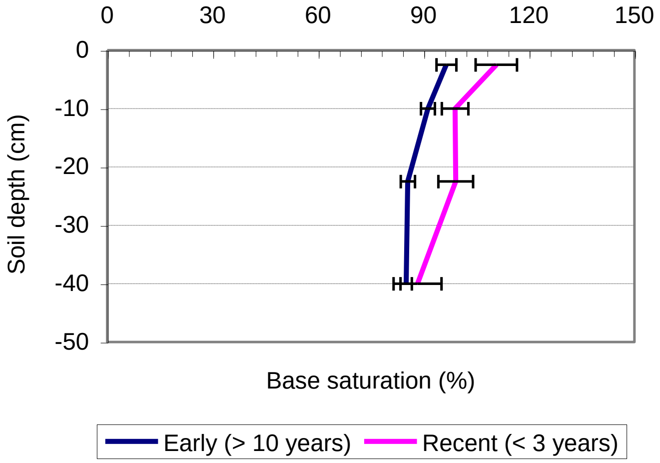


Figure 6.14 Effects of length of time for which mechanized practices have been implemented on base saturation (%) of P soil of Mauritius cropped with sugar cane

The very high base saturation values in the recently-mechanized fields demonstrate that there were large amounts of bases, essentially from the organic amendments added during land preparation. Thereafter, bases were lost from the topsoil through crop removal and leaching, leading to a decrease with time in the upper 30 cm.

6.4 Conclusion

The changes that occurred in the chemical properties of the major soils of Mauritius as a result of sugar cane cropping were in line with those occurring in their biological properties. The differences tended to be related to the climatic zone, since cultural practices that affect the soil’s chemistry, such as liming, vary depending on prevailing climatic conditions. As noted with respect to the biological properties of the soil, sugar cane cropping did not degrade the soil. In fact, the addition of agrochemicals and amendments often improved the soil, even though such additions did not always adequately compensate for the removal of nutrients by the crop or by natural agents such as water. The adoption of mechanized practices did not have a negative impact on most soil chemical properties. In fact, chemical properties were improved with mechanization in the P soil of Médine. The latter stands apart from the other sites as innovative soil treatments and amendments were used to negate the impact of land preparation and rock removal, leading to a better chemical status.

With respect to time under cropping, the results indicate that the changes in chemical properties were not the same for the rock-free soil and the rocky one. Again, the innovative soil treatments and amendments at Médine have impacted positively on the chemistry of the rocky soil in the long term whereas there has been a general degradation with time in the rock-free soil. Under long-term mechanized practices, the situation was also one of inevitably lower soil chemical quality as a result of the policy of adding large amounts of chemical amendments to the soil at the time of land preparation to rapidly boost its quality, followed by a depletion of the bases with time, so that the soil became chemically poorer in the long-term.

CHAPTER 7

INFLUENCE OF SUGAR CANE PRODUCTION ON SOME SOIL PHYSICAL PARAMETERS

7.1 Introduction

Industrial sugar cane production is not possible today without modern husbandry practices, particularly through the use of machines such as tractors and tillage implements for land preparation and harvesters for cane cutting. Machinery traffic is common within sugar cane fields and this, as expected, has affected the physical properties of the soil mainly through compaction (Ng Cheong *et al*., 1999), which led to an increase in bulk density and a reduction in soil porosity. There was previously little change in bulk density in the cane soils of Mauritius (Wong You Cheong and Chan, 1977) as cropping practices were exclusively manual. Compaction as a consequence of mechanization is consistent with what was found elsewhere (e.g. McLean, 1975; Wood, 1985; Van Antwerpen and Meyer, 1996). As would be expected, it was more pronounced in the sugar cane inter-row (McGarry *et al*., 1996, Hartemink, 1998b) where most compacting forces are applied to the soil. Moreover, compaction was also observed in the subsoil (Henry and Ellis, 1996), indicating that machinery traffic was not the only contributing factor.

Besides compaction, the mechanized practices in sugar cane production could lead to the physical degradation of the soil surface, resulting in lower macro-porosity and permeability. As a result, the stabilized infiltration rate of a soil planted with sugar cane tended to be lower than that of a soil under native vegetation (Garside *et al*., 1997, Hartemink, 1998b). The adverse effect of traffic in this respect was further highlighted by observation that the stabilized infiltration rate in parts of sugar cane fields not subjected to traffic was no different from that of areas under native vegetation (Hartemink, 1998b). In Mauritius, stabilized infiltration rate was also much lower for sugar cane inter-rows subjected to harvester traffic compared to inter-rows that had been traffic-free (Ng Cheong *et al*., 1999).

While the stabilized infiltration rate of water into the soil was undoubtedly reduced by the machinery traffic associated with sugar cane cultivation, there was no such clear-cut effect with respect to the soil's plant available water. There could be significant increases (Van Antwerpen and Meyer, 1996), or significant decreases (Garside *et al*., 1997, McGarry and Bristow, 2001) or no difference at all (Masilaca *et al*., 1986, Henry and Ellis, 1996). As far as Mauritius is concerned, sugar cane cultivation had variable effects on this soil property (Wong You Cheong and Chan, 1977). In general, plant available water decreased with sugar cane cultivation in soils in dry areas, but increased for a soil in a wet area. These differences could have been caused by changes in soil texture.

The effect of sugar cane cultivation on aggregate stability was more obvious. The evidence suggests that aggregates found close to the soil surface became less stable when soils were cropped with sugar cane, be it in Mauritius (Wong You Cheong and Chan, 1977) or elsewhere (McGarry *et al*., 1996). Furthermore, soil aggregates tended to become less stable the longer the soil was cultivated with sugar cane (Qongqo and Van Antwerpen, 2000).

It appears on the other hand that sugar cane cultivation did not affect soil texture, given that the particle size distribution of sugar cane-planted soils did not differ greatly from that of soils under native vegetation in Australia and South Africa (McLean, 1975; Van Antwerpen and Meyer, 1996, McGarry and Bristow, 2001). This was not the case in Mauritius where sugar cane cropping led to significant, but opposing, effects on clay content in two zones with marked differences in rainfall and temperature (Wong You Cheong and Chan, 1977). However, no explanation was found to explain those differences.

A review of the literature has thus shown that sugar cane production had mostly detrimental effects on soil physical properties in Mauritius and in other sugar cane producing countries. The main cause appeared to be in-field traffic, whose disrupting effects have impacted negatively on the soil's matrix and porosity. The demands of modern agriculture necessitate the use of high inputs, particularly in terms of energy. The downside of this practice appears to be a physical degradation of the soil when this energy is applied on its surface.

In this chapter, the effects of sugar cane cropping on some physical properties of the major soils of Mauritius are reported. The six indicators of physical quality were particle size distribution, aggregate size distribution and stability, bulk density, plant available water and stabilized water infiltration rate. The changes resulting from manual and mechanized sugar cane cropping on all five major soil groups are presented. In addition, the effects of time under manual and mechanized sugar cane cropping practices for selected soil groups are also dealt with.

7.2 Procedure

7.2.1. General

Physical soil quality parameters under study were particle size distribution, aggregate size distribution, water stability of aggregates, bulk density, plant available water and stabilized infiltration rate. A complete description of the methodology used to determine these six parameters has been given in Chapter 4.

All the measurements of physical soil quality parameters had required the removal of the non-soil fraction by sieving through a 2 mm mesh prior to analysis, except for the stabilized infiltration rate which was measured *in situ*. For particle size distribution, aggregate size distribution and water stability of aggregates, the results derived from the sieved material needed no further data manipulation since these three parameters were concerned solely per size fraction. On the other hand, the bulk density and plant available water parameters needed to be calculated on a bulk soil basis. In these two cases, the non-soil fraction had to be taken into account as gravel and cobbles occupied a certain proportion of the whole soil volume. As far as bulk density was concerned, a correction factor was already applied in the determination procedure, as described in Section 4.5.9. With respect to PAW, it has been assumed that though the stone fraction of the sample did not retain water, it occupied a given volume making it necessary to apply a correction factor. This volume of stones was taken to be the volume measured in the course of bulk density determination. Thus, in samples where stones were present, Equation 4.1 to calculate PAW was modified to Equation 7.1 to take into consideration the stone content of the bulk soil sample.

$$\text{PAW} = 0.1\,(\text{FC} - \text{PWP}) \times \text{BD} \times (1 - \text{stone content}) \times \text{soil depth} \tag{7.1}$$

where PAW is plant available water in mm; FC is field capacity in % in gravimetric terms; PWP is permanent wilting point in % in gravimetric terms; BD is bulk density in g cm^{-3}; stone content is a non-dimensional fraction; and soil depth is in cm.

7.2.2 Data processing and analysis

The same procedure as described in Section 5.2.2 has been adopted to calculate the average value of the measurements and their standard error, giving a single representative point per parameter encompassing all the variability of the result.

7.2.3 Data presentation

Particle size distribution differed substantially from the other physical parameters in that it is made up of relative proportions of sand, silt and clay, and was therefore expressed as relative percentages rather than absolute values. It was first represented as vertical bar charts for the total 50 cm of soil, calculated as a weighted average of the samples from the four different layers. It has also been presented as horizontal bar charts layer-wise, with the soil layer on the y-axis and particle size distribution on the x-axis. Given the nature of the graphs, it has not been possible to present the standard error with the average percentage values. For aggregate size distribution, water stability of aggregates and bulk density, the data have been displayed in a line graph, the evolution of each parameter with depth being shown on the x-axis with soil depth on the y-axis. The horizontal error bars showed the standard error at each data point. On the other hand, the plant available water and the stabilized infiltration rate have been displayed in the shape of vertical bar charts with vertical standard error bars.

7.3 Results and discussion

7.3.1 Particle size distribution

7.3.1.1 Effects of manual and mechanized sugar cane cropping practices on particle size distribution

The evolution of the particle size distribution of the five major soil groups of Mauritius following sugar cane cropping and the adoption of mechanized practices are shown in Figures 7.1 per bulk soil and in Figure 7.2 per soil layer. Average values with their standard errors are presented in Appendix 1.

In general, the soils contained relatively high proportions of clay (Figure 7.1). In fact, they all had a texture that could be classified as silty clay according to the USDA system (Gee and Bauder, 1986), irrespective of treatment. The exceptions were the F soil, which was classified as clay loam in all treatments and the B soil under native vegetation, which also fell in this textural class. The L soil contained the highest, and the F soil the lowest, proportion of clay, some 70% and 30% respectively. The highest silt content, which was around 30%, was found in the F soil, which was the only one with almost equal proportions of the three particle sizes. The textural classes of the soil layers were similar to those of the bulk soil. There was no abrupt change in the relative proportions of the three particle sizes down the profile in all five soils (Figure 7.2). However, even though these changes were gradual, the trends were different depending on soil group. Thus, in the soils under native vegetation, there was a small increase in clay content down the profile for the P, L and H soils. The opposite was true for the F soil, while the texture of the B soil was uniform throughout the profile.

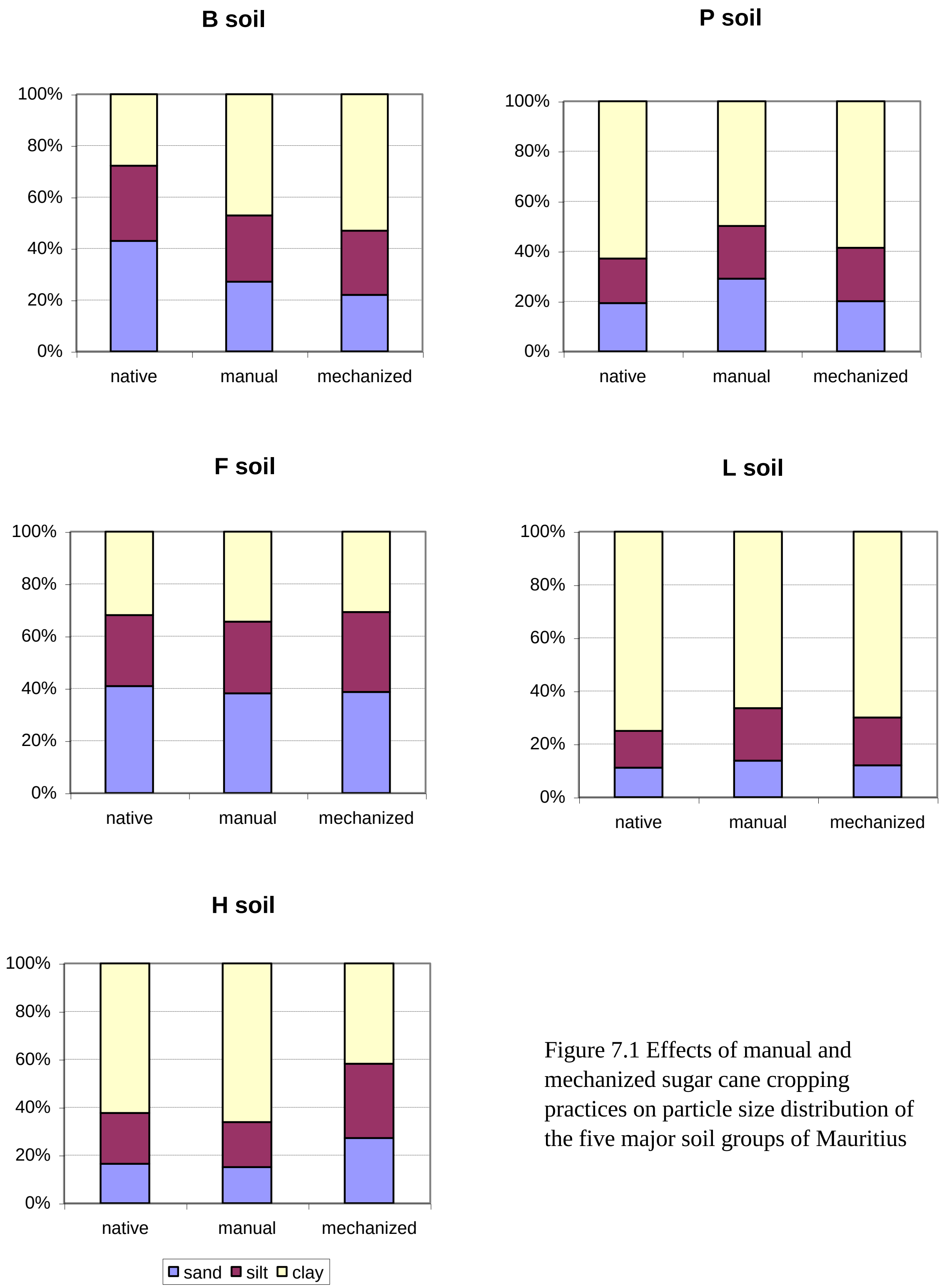


Figure 7.1 Effects of manual and mechanized sugar cane cropping practices on particle size distribution of the five major soil groups of Mauritius

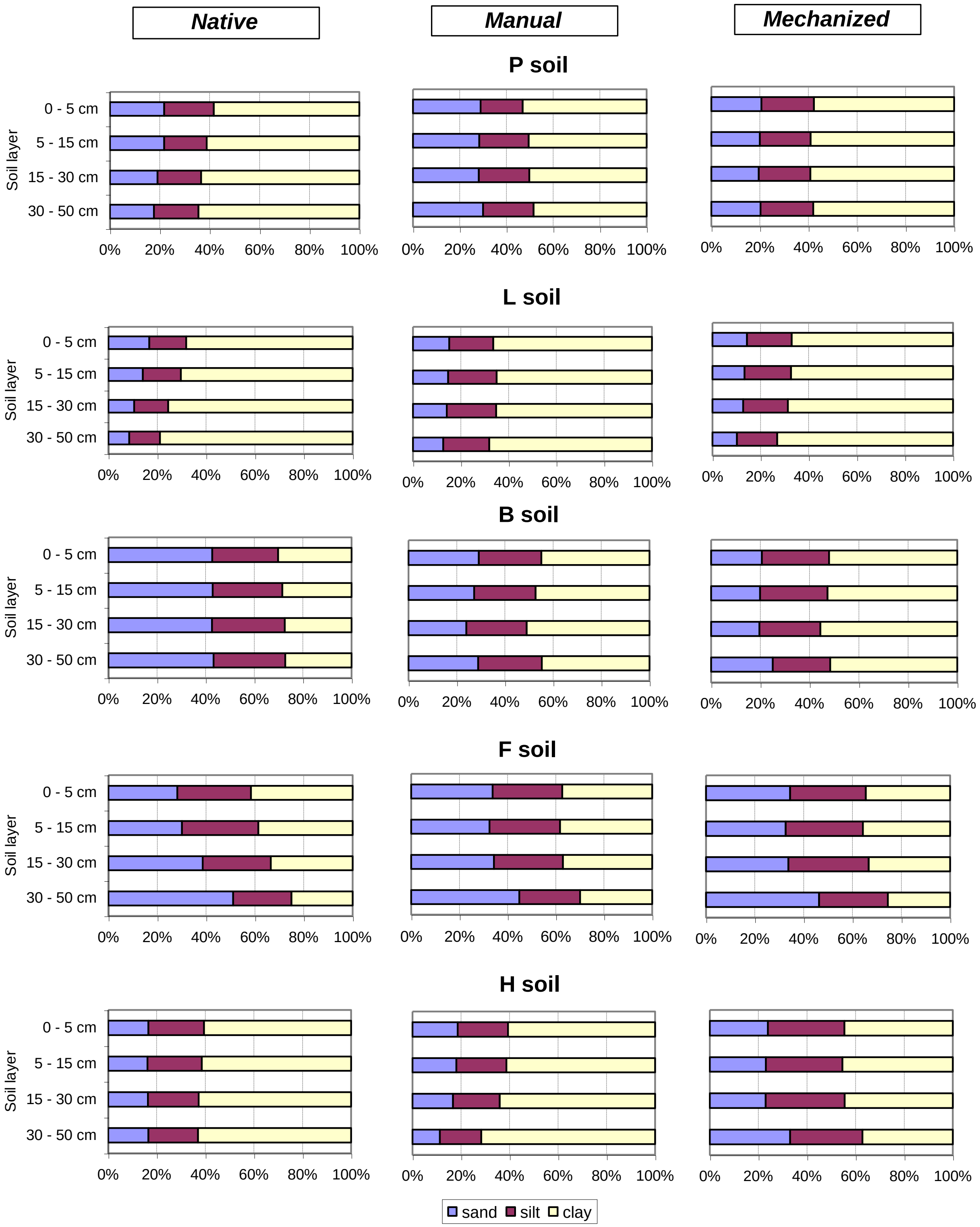


Figure 7.2 Effects of manual and mechanized sugar cane cropping practices on particle size distribution of soil layers of the five major soil groups of Mauritius

The effect of sugar cane cropping on particle size distribution was variable. In the bulk soil, it led to a marked increase in clay content and concomitant decrease in sand content in the B soil, but had an opposite effect on the P and L soils, whereas the F and H soils were not affected. Silt contents did not change with cropping, except for an increase in the L soil. The reduction in clay content that occurred within the bulk of the P and L soils was associated with a general reduction in all layers. In the B soil, the highly significant increase in clay content noted in the bulk soil also reflected itself in all layers but the change was more pronounced in the deeper layers. In the F and H soils, there were small, but sometimes statistically significant, variations in texture across the soil layers, with a certain degree of clay enrichment in the deeper layers of both soils.

Effects of mechanized practices on particle size distribution were also variable. There was a slight increase in clay content and decrease in sand content with mechanization in the B and L soils, and a similar, but more pronounced, effect on the P soil. No difference was noted with the F soil, but there was a marked decrease in clay content in the H soil, with a simultaneous increase in both silt and sand contents. Layer-wise, clay content increased in a regular way across the profile of the P soil. Similarly, there was a small but regular increase in clay content and decrease in sand content throughout the profile of the B and L soils. As with bulk soil, the layers of F soil were not affected. However, the marked decrease in clay and increase in silt and sand contents in the H soil were more pronounced in the deeper layers.

The reduction in clay content in the sub-humid P and L soils as a result of sugar cane cropping could have been caused by wind erosion of the fine-textured material when the soil was left bare and dry after harvest, particularly if residues were burnt (Brye, 2003). The other possible explanation is associated with intensive irrigation under cropped conditions, which could lead to preferential clay loss in surface eroded sediments (Lal, 1976). The fact that this reduction in clay particles was more important in the lower horizons probably showed the effects of tillage, with clay being brought up from the lower horizons into the upper ones, where it became more susceptible to the loss process described. Furthermore, the increase in clay content associated with mechanized practices in both soils of the sub-humid zone indicates that there was a beneficial effect from the trash blanketing that resulted from mechanized harvest. This protective trash blanket has shielded the soil surface against the loss of fine material, directly by its covering effect, and indirectly by preserving soil moisture. Clay increase associated with mechanized practices in the B soil was probably caused by the production of particles of smaller size fractions from larger ones as a result of physical breakdown from repeated mechanical disturbance (Brye, 2003) whereas clay decrease in the H soil could have been caused by its illuviation down the profile (Lal, 1997).

7.3.1.2 Particle size distribution and length of time during which sugar cane has been cropped manually

The effects of length of time under cultivation on the particle size distribution of the two major soil groups of the sub-humid zone of Mauritius are shown in Figure 7.3 for the bulk soils and Figure 7.4 for the soil layers. The clay content in the P soil decreased and its sand content increased significantly with time, while the opposite trend was observed for the L soil, but without any significant difference. The proportion of silt remained unchanged for both soils. Layer-wise, the same trends have been noted. Thus, the texture of the L soil was not affected by time under cultivation while the P soil accumulated more coarse particles with time at the expense of the finer ones. As sugar cane cultivation itself has already been shown to significantly reduce clay content in both sub-humid soils (Figure 7.1), it can be concluded that the process leading to loss of clay took place in the P soil when native vegetation was replaced by sugar cane. However, the loss was a slow process as indicated by the similar clay percentage in the soil cultivated for less than 25 years. The processes involved in this gradual loss of clay have already been discussed in the preceding Section.

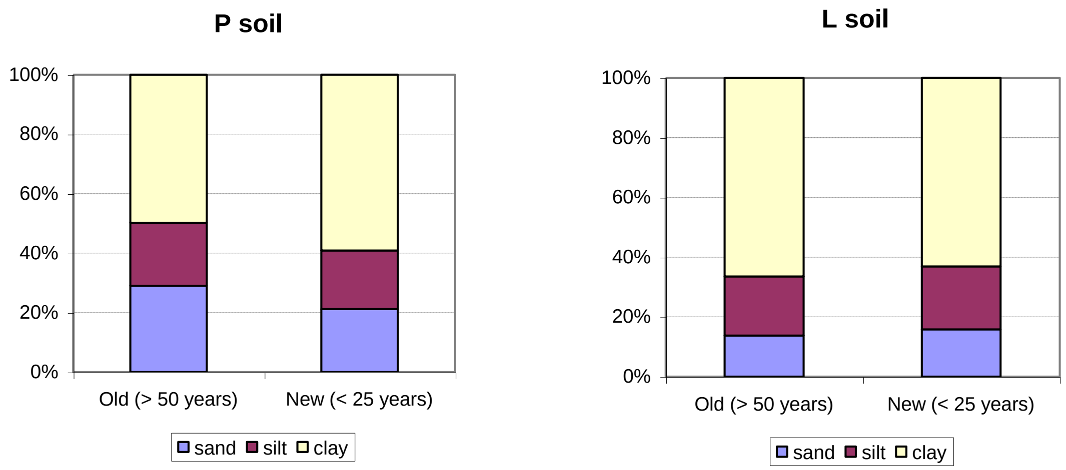


Figure 7.3 Effects of length of time under manual sugar cane cropping on particle size distribution of the two major soil groups in the sub-humid zone of Mauritius

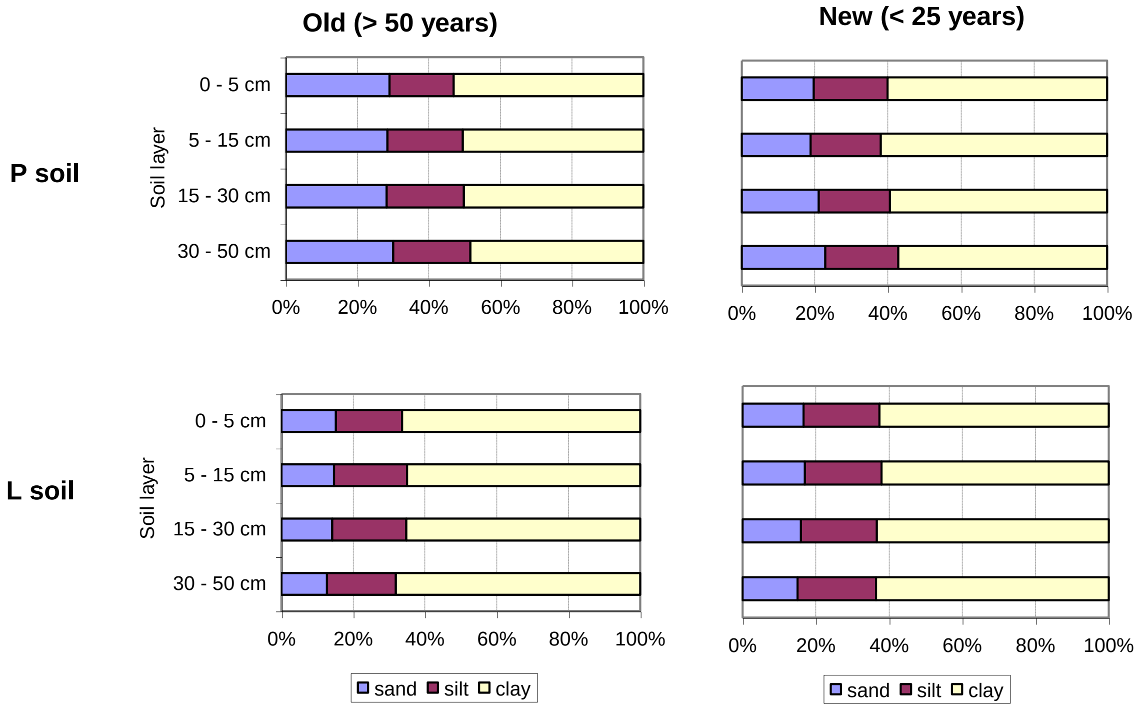


Figure 7.4 Effects of length of time under manual sugar cane cropping on particle size distribution of soil layers of the two major soil groups in the sub-humid zone of Mauritius

7.3.1.3 Particle size distribution and length of time during which mechanized practices have been adopted

The effects of time under mechanized practices on the particle size distribution of the P soil are shown in Figure 7.5 for the bulk soil and Figure 7.6 for individual soil layers. Overall, clay content decreased with time while sand content increased and silt content remained unchanged. However, only the increase in the sand fraction was significant. The relatively insignificant nature of the changes has been further confirmed by the measurements from individual soil layers, where a slight decrease in clay and increase in sand fraction were found in all soil layers, but these differences were not significant. There has therefore been little change in soil texture with time with mechanized operations.

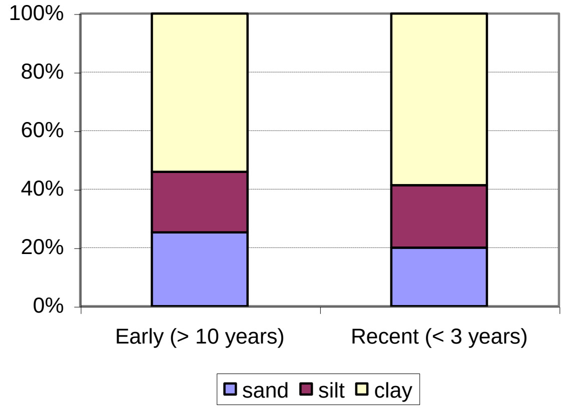


Figure 7.5 Effects of length of time for which mechanized practices have been implemented on particle size distribution of P soil of Mauritius cropped with sugar cane

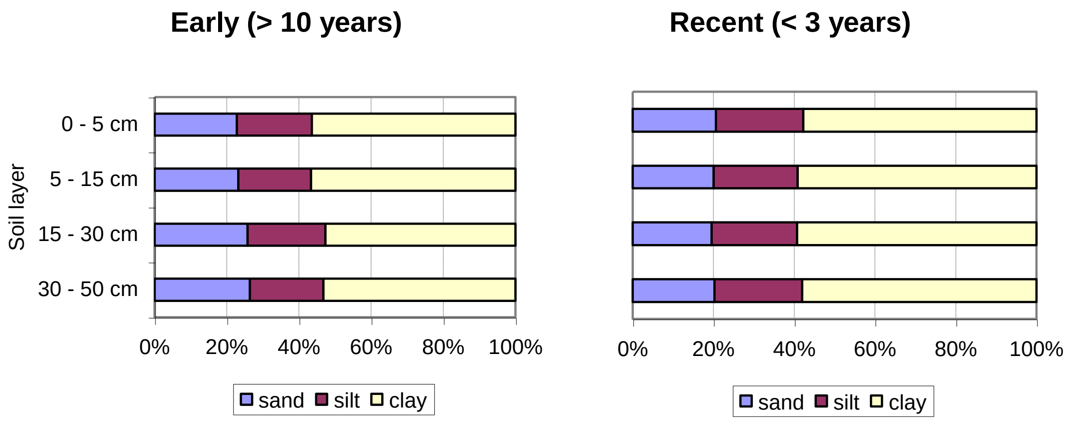


Figure 7.6 Effects of length of time for which mechanized practices have been implemented on particle size distribution of soil layers of P soil of Mauritius cropped with sugar cane

7.3.2 Aggregate size distribution

7.3.2.1 Effects of manual and mechanized sugar cane cropping practices on aggregate size distribution

Under native vegetation, the size of aggregates in the sub-humid L and P soils increased with depth. The geometric mean diameter (GMD) values increased from 0.8 mm in the topsoil to 1.1 and 1.3 mm in the subsoil of the L and P soils respectively (Figure 7.7). These aggregates were smaller than those of the H and F soils, the latter having a relatively constant average GMD of some 1.5 mm. The B soil had intermediate aggregate sizes, its GMD decreasing from 1.5 mm in the topsoil to 1.0 mm in the subsoil. As opposed to the sub-humid L and P soils, the aggregates from the wetter areas tended to become smaller down the profile, this evolution being more pronounced in the B than the F or H soils.

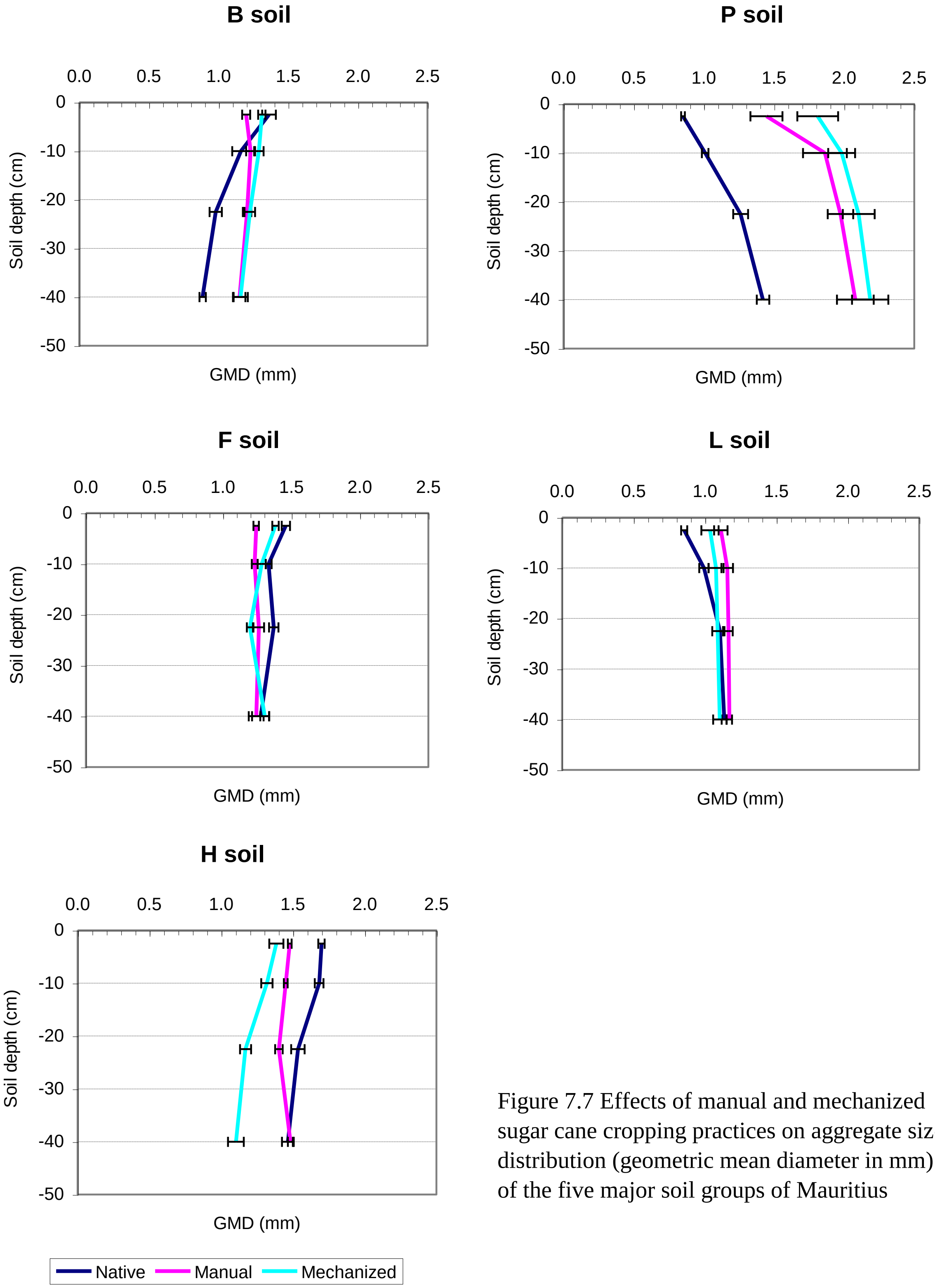


Figure 7.7 Effects of manual and mechanized sugar cane cropping practices on aggregate size distribution (geometric mean diameter in mm) of the five major soil groups of Mauritius

Changes in aggregate size distribution as a result of sugar cane cropping were not consistent in all soils. Cropping led to aggregates of higher GMD in the sub-humid soils and to aggregates of lower GMD in the H and F soils while the GMD of the aggregates in the B soil evolved differently going down the profile. The greatest change occurred in the P soil where the GMD increased significantly across the profile by some 50% when it was cropped with sugar cane. The increase to a much smaller extent was also significant in the L topsoil. On the other hand, there were relatively small but significant drops in aggregate size in the F and H topsoil. Finally, cropping significantly decreased aggregate size in the B topsoil, but increased it significantly deeper in the profile.

The adoption of mechanized practices led to variable changes in aggregate size distribution. Thus, higher GMD values were found in the topsoil in the mechanized treatments of both P and B soils, but there was no significant effect deeper in the profile. On the other hand, there was a significant decrease in GMD in the whole soil profile for the L and H soils. As for the F soil, the trend was for an increased aggregate size distribution.

No reported work of the effects of sugar cane cropping on aggregate size distribution was found in the literature because it is difficult to relate aggregate size to field phenomena, most investigators preferring to use aggregate stability rather than aggregate size distribution as an index of soil structure in the field (Kemper and Rosenau, 1986). Nevertheless, the simultaneous determination of these two parameters was desirable to provide a more complete picture of the soil structure. In the present study, sub-humid L and P soils that were cropped with sugar cane using manual practices had larger aggregates than the same soils under native vegetation. Apart from the usual cultural practices associated with cultivation, i.e. tillage, fertilization and crop protection measures, the main difference between virgin and cultivated soils in the sub-humid L and P soils was the provision of irrigation. Without irrigation, sugar cane could not be profitably produced in the sub-humid zone, as lack of water is the main obstacle to plant growth. Irrigation is therefore a pre-requisite for rendering the L and P soils suitable for sugar cane production (Arlidge, 1973). With irrigation, there has been an increased production of plant biomass, and in the case of sugar cane, the combined effect of cane roots and residue return must have promoted the formation of larger aggregates. Roots enmesh and realign soil particles, release exudates, and aggregation is enhanced with the increasing root length density, microbial associations and ground cover (Bronick and Lal, 2005). In contrast to the irrigated soils of the sub-humid zones, the humid H and the super-humid F and B soils had a naturally high plant cover under native vegetation, thanks to the high rainfall prevailing in those regions. Sugar cane cultivation was therefore unlikely to have produced substantially more roots or residues than the amount already present under natural conditions. This was substantiated by the higher OM content under native vegetation in those soils (Figure 5.1). One would not therefore expect to note an increase in aggregate size in those soils. In fact, aggregates were relatively smaller with sugar cane cropping in the top 30 cm of the H and F soils, probably because they had been broken by soil tillage within this zone and were left exposed to the vagaries of weather. A regular wetting and drying cycle occurs under natural conditions in these regions and this wet-dry cycle has probably led to disruption of the aggregates as reported by Singer *et al*. (1992).

With respect to the adoption of mechanized practices, it appeared that, irrespective of climatic zones, rock content played a part in changes of aggregate size distribution as the rocky P and B soils were affected in very similar ways. There was no significant difference in their subsoil but aggregates were bigger following mechanization in their topsoil, presumably on account of superficial soil consolidation with harvester traffic. For the rock-free L and H soils, the presence of smaller aggregates when mechanized practices were adopted could be ascribed to aggregate degradation caused by harvester and in-field loader traffic, exacerbated by a significant fall in OM content. For the F soil, the increased aggregate size with mechanization was probably due to the increase in OC content within the topsoil of this treatment compared to the manually cropped soil (Figure 5.1).

7.3.2.2 Aggregate size distribution and length of time during which sugar cane has been cropped manually

The aggregates of the P soil were much larger than those of the L soil, irrespective of time under cultivation (Figure 7.8). Aggregates became smaller the longer the soils had been under sugar cane cultivation. This change was not significant in both topsoil, but became significant in the subsoil.

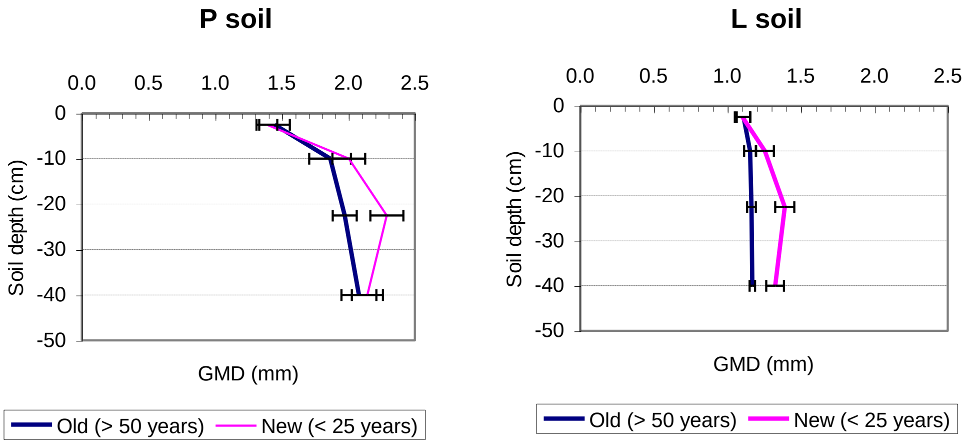


Figure 7.8 Effects of length of time under manual sugar cane cropping on aggregate size distribution (geometric mean diameter in mm) of the two major soil groups in the sub-humid zone of Mauritius

7.3.2.3 Aggregate size distribution and length of time during which mechanized practices have been adopted

The P soil where mechanized practices had recently been implemented had aggregates of lower GMD than the soil where mechanization had been adopted for a longer period (Figure 7.9). However, the changes in aggregate size distribution were not significant. It is therefore clear that, as with time under cropping, it does not matter how long the P soil has been under mechanized practices, as its aggregate size distribution would be unaffected.

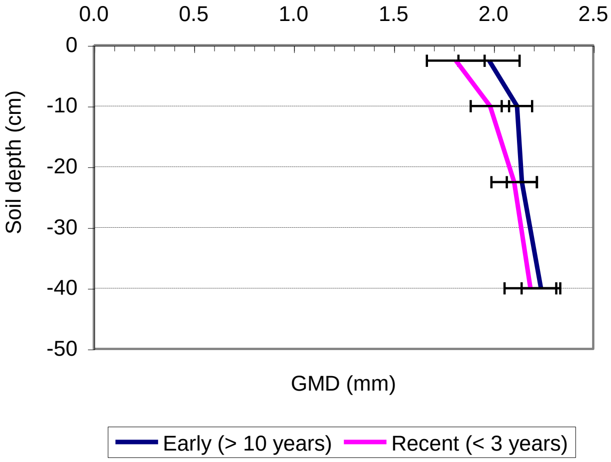


Figure 7.9 Effects of length of time for which mechanized practices have been implemented on aggregate size distribution (geometric mean diameter in mm) of P soil of Mauritius cropped with sugar cane

7.3.3 Water stability of aggregates

7.3.3.1 Effects of manual and mechanized sugar cane cropping practices on the water stability of aggregates

The index for water stability of aggregates ranges from 0 to 1. A zero value indicates total aggregate breakdown when flooded, while an index of 1 refers to the aggregate remaining completely stable in water. Under native vegetation, the aggregate stability index of the sub-humid L and P soils was much lower than that of the humid H and super-humid F and B soils. Thus, for the P and L soils, the peak index value was of the order of 0.6 and 0.7 respectively, compared to about 1.0 for the other three soils (Figure 7.10). In addition, their aggregate stability decreased with depth, values as low as 0.2 being noted for the P and L subsoil. On the other hand, the stability index of the super-humid B and F soils stayed constant at about 1.0 for the whole profile. The humid H soil resembled the sub-humid soils in that it displayed a gradual decrease in stability index down the profile.

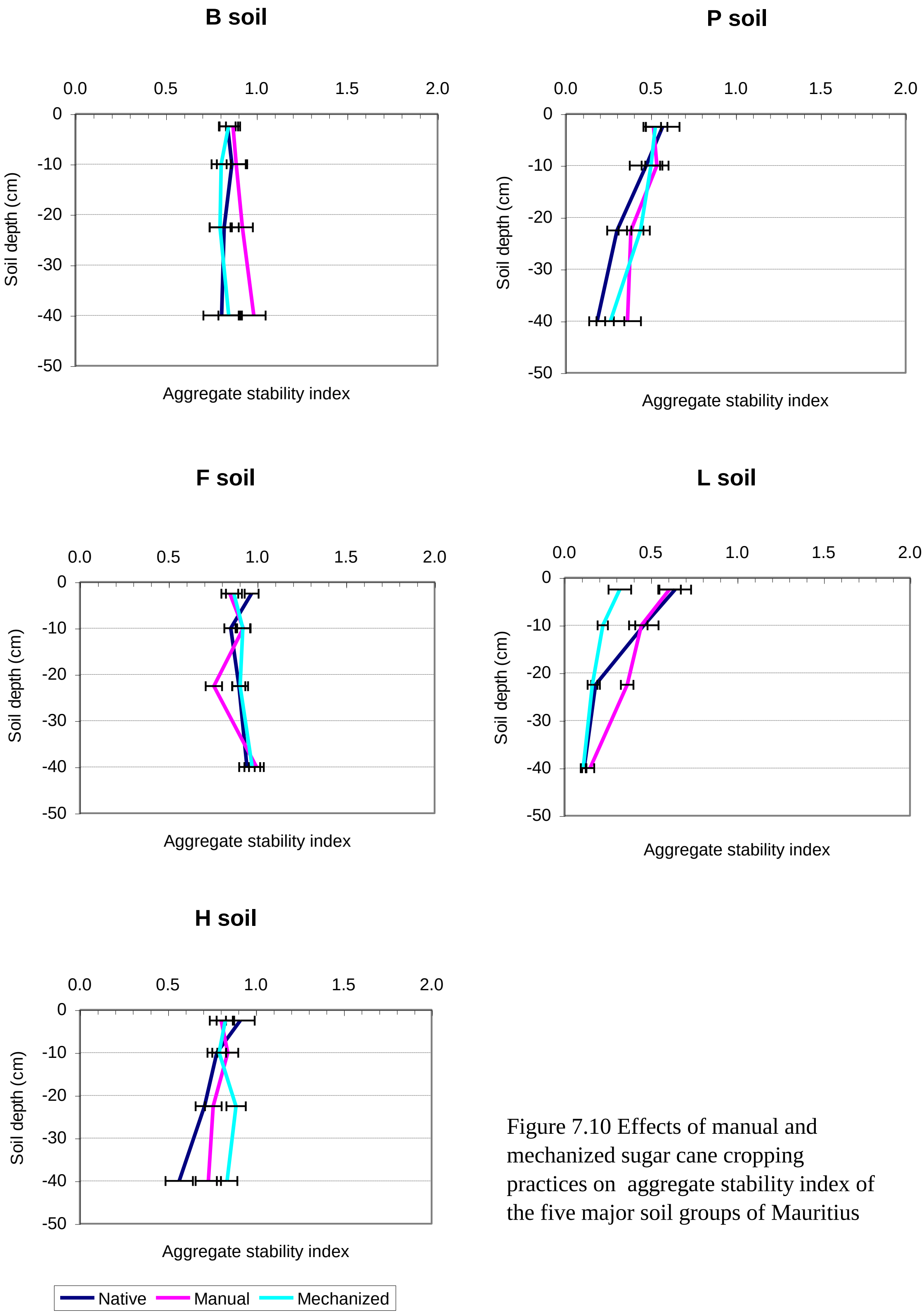


Figure 7.10 Effects of manual and mechanized sugar cane cropping practices on aggregate stability index of the five major soil groups of Mauritius

When sugar cane was planted, the only significant effect was an increase in aggregate stability in the P, L, B and H subsoil. The F soil was the only one to be affected negatively by cultivation, with significant decreases in stability index in parts of the topsoil and the subsoil.

With the adoption of mechanized practices, the stability index of the P soil was not significantly affected whereas that of the L soil was significantly reduced in most of the soil profile. There was also a general trend towards lower stability in the B soil with the adoption of mechanized practices, but this decrease was significant only in the subsoil. The opposite was true for the F and H soils, where the general trend was for a higher stability index, with a significant increase in the subsoil.

As reviewed by Bronick and Lal (2005), aggregate stability can be used as an indicator of soil structure. Aggregation results from flocculation, cementation and rearrangement of particles. It is mediated by soil organic carbon, biota, ionic bridging, clay and carbonates. As far as sugar cane is concerned, the evidence from the literature is that aggregate stability of the soils decreased with long-term cultivation as a consequence of their declining organic matter content (Wong You Cheong and Chan, 1977; Qongqo and Van Antwerpen, 2000; Dominy *et al*., 2001). The results from this study contradict these literature findings since aggregate stability did not seem to be susceptible to changes upon cultivation. On the contrary, aggregate stability tended to increase, as were the case in the subsoil of the P, L, B and H soils. This enhancing effect could be ascribed to the fact that, with soil tillage, OM tended to be incorporated deeper in the profile (Figure 5.1), thereby increasing the stability of the aggregates in the lower layers. On the other hand, the significant decrease noted in the F soil could be ascribed to a marked decline in OM in its topsoil, but no such OM depletion was observed to explain the lower stability of its subsoil. In this instance, the decrease in stability had to be ascribed to a different cause, such as the action of cultivation impacting on aggregate stability by breaking up aggregates via roots and fungal hyphae and by direct shattering of aggregates. It must also be remembered that organic carbon is not the only element influencing aggregate stability, as demonstrated by Blair (2000).

The adoption of mechanized practices had relatively small effects on aggregate stability, apart in the L soil where the topsoil was degraded. Of all the soils of Mauritius, this soil group had the lowest OM content, which was further reduced with mechanization. It is possible that its OM content had fallen below a critical threshold beyond which stability was impaired, whereas in the other soils, a sufficiently high OM content persisted to maintain their aggregate stability. Added to this SOM factor was the additional stress created by the passes of harvesters and associated traffic.

7.3.3.2 Water stability of aggregates and length of time during which sugar cane has been cropped manually

Even though aggregate stability values remained relatively low, the length of time under sugar cane cropping clearly led to a higher stability index in the sub-humid zone (Figure 7.11).

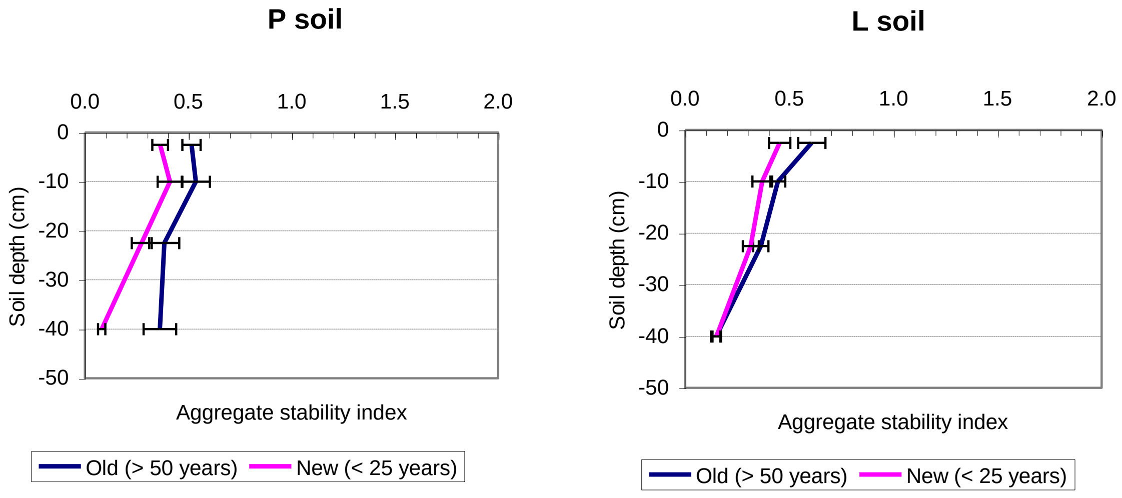


Figure 7.11 Effects of length of time under manual sugar cane cropping on aggregate stability index of the two major soil groups in the sub-humid zone of Mauritius

Both P and L soils displayed higher stability values near the surface of the old cultivated treatment, which had been under cane for more than 50 years. The increase with time was significant in part of the P topsoil and its subsoil, and in part of the L topsoil. Such changes could be directly related to the OM content of the respective layers in the two soils, since the old cultivated treatments had a higher OC content in the topsoil of both P and L soils, while the P soil also had a higher content in its subsoil, compared to the new fields, which had been under cane for less than 25 years (Figure 5.4).

7.3.3.3 Water stability of aggregates and length of time during which mechanized practices have been adopted

The aggregate stability index of the P soil irrespective of depth was not significantly affected by the number of years during which mechanized operations had been practised (Figure 7.12).

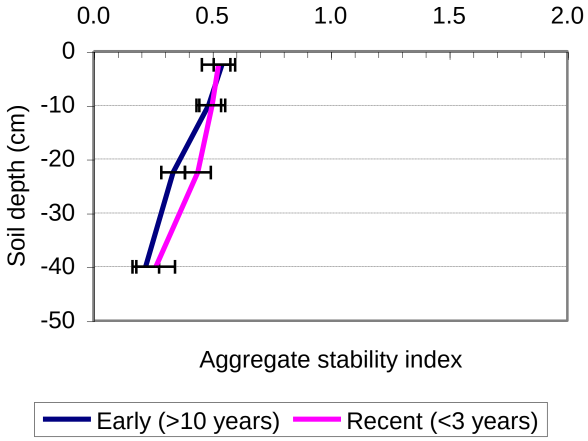


Figure 7.12 Effects of length of time for which mechanized practices have been implemented on aggregate stability index of P soil of Mauritius cropped with sugar cane

However, there was a trend whereby the aggregate stability decreased in the deeper horizons, mirroring a similar decline in SOM (Figure 5.5).

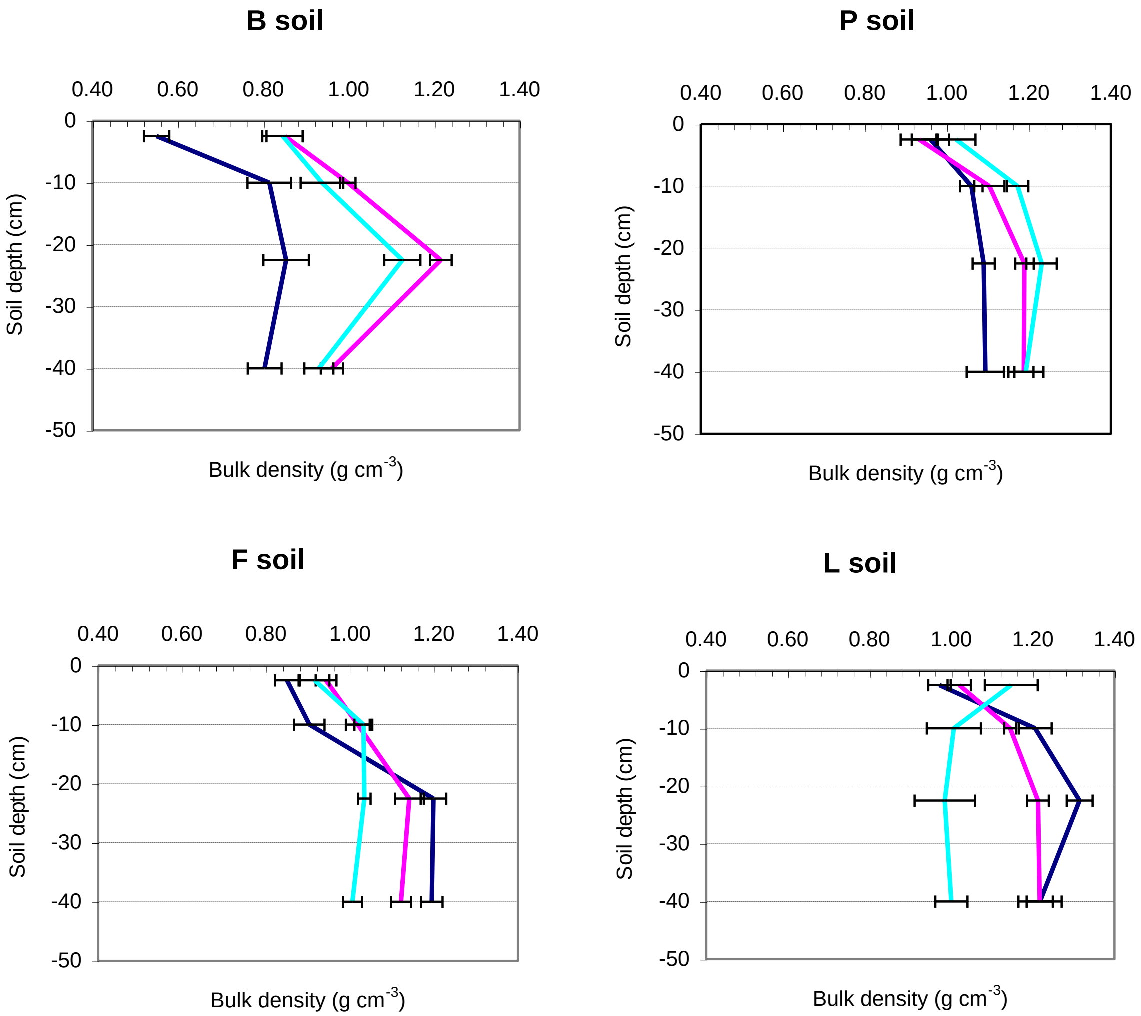
7.3.4 Bulk density

7.3.4.1 Effects of manual and mechanized sugar cane cropping practices on bulk density

In general, all the soils were more compact with increasing depth under native vegetation (Figure 7.13). There was a marked increase in topsoil bulk density, below which bulk density values tended to be relatively constant. Values were relatively low, as would be expected with silty clay soils, and did not exceed 1.3 g cm^{-3}. The rocky soils had a lower bulk density than the rock-free ones. The bulk density of the B soil ranged from 0.6 to 0.8 g cm^{-3}, while that of the P soil ranged from 0.9 to 1.0 g cm^{-3}. In contrast, the value for the F soil ranged from 0.8 to 1.2 g cm^{-3}, while that of the L soil lay between 1.0 and 1.3 g cm^{-3}.

The changes in bulk density induced by cropping were variable and seemed to be influenced by rock content. In the rocky P and B soils, the general trend was for a higher bulk density with cultivation, i.e. soil compaction. Thus, in the P soil, bulk density increased significantly in the subsoil. The compaction was even more pronounced in the B soil where there was a significant increase in bulk density down the profile. The extent of compaction was much higher than in the P soil, with maximum bulk density increases of the order of 0.4 g cm^{-3}, while the corresponding maximum increase in the P soil did not exceed 0.2 g cm^{-3}. For the rock-free L soil, the trend was for loosening in part of the topsoil and of the subsoil. The F soil, for its part, displayed both compacting and loosening effects with sugar cane cropping. Indeed, while there were significant increases in bulk density in the topsoil, significant bulk density decreases were noted in the subsoil. The H soil was similar to the rocky P soil, with no change in bulk density in the topsoil, but significant compaction deeper in the profile.

Adopting mechanized practices led to compaction in the whole profile of the H soil. The P soil was also compacted, even though a significant increase in bulk density was noted only in the topsoil. For the super-humid B and F soils, the general trend was for a lower bulk density with mechanized operations in the subsoil, while the topsoil was not affected. The effects of



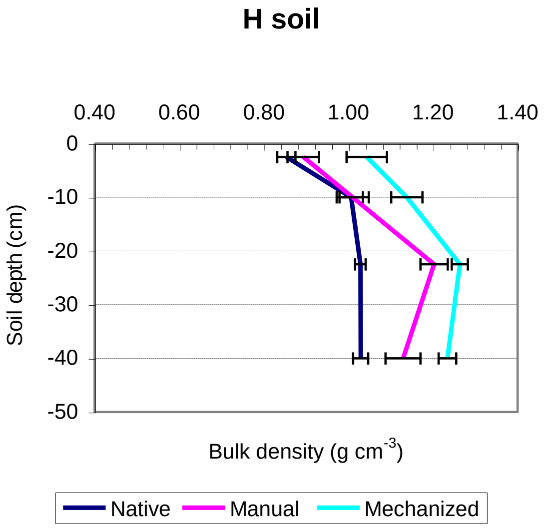


Figure 7.13 Effects of manual and mechanized sugar cane cropping practices on bulk density of the five major soil groups of Mauritius

mechanized practices on the L soil were not uniform, as bulk density was significantly higher in the topsoil, but lower in the deeper layers.

Soil compaction is the process by which soil grains are rearranged to decrease void space and to bring them into closer contact with one another, thereby increasing the bulk density. As reviewed by Hamza and Anderson (2005), bulk density is the most frequently used parameter to characterize the state of soil compactness. With respect to sugar cane cultivation, the available evidence was that soils were compacted when they were cropped with sugar cane (e.g. Wood, 1985; Van Antwerpen and Meyer, 1996), the main cause being the pressure applied to the soil upon traffic by wheeled farm machines. This process was probably the main cause of compaction in the P, B and H soils. Tillage has also been identified as another possible cause for subsoil compaction, with more significant effects if the soil was tilled under wet conditions (Hamza and Anderson, 2005). The lower bulk density in some subsoil layers of the rock-free L and F soils upon sugar cane cultivation was probably due to the use of subsoilers and other soil loosening equipment at the time of land preparation, a practice that was more difficult to implement in the rocky P and B soils.

The effects of mechanized practices on soil bulk density corresponded to observations from other sugar cane producing countries, namely that the introduction of mechanized harvesting has led to topsoil compaction. The fact that compaction occurred with mechanized harvesting down to a depth of about 20 cm, beyond which the soil remained relatively unscathed, had already been noted in Mauritius (Ng Cheong *et al*., 1999). This topsoil compaction was related to the contact pressure applied to the ground by the axles of the harvesters and their accompanying sugar cane bins, which got more and more loaded as harvest progressed. On the other hand, the subsoil loosening in the rock-free L and F soils was probably caused by subsoiling, as additional subsoiler passes were often made in mechanically-harvested fields to alleviate any perceived compaction.

7.3.4.2 Bulk density and length of time during which sugar cane has been cropped manually

In the rock-free L soil, the bulk density decreased the longer the field has been under cane cropping (Figure 7.14). This significant loosening effect as a function of time occurred throughout the whole profile. Possible causes for this decrease could be physical, e.g. enhanced wetting and drying because of intensive irrigation, or biological, e.g. increased earthworm activity and root growth thanks to wetter soil conditions. However, it is more likely that it was caused by human intervention. Indeed, bulk density decreased in this soil on account of tillage when native vegetation was replaced by the sugar cane crop. The cumulative effects of tillage over time probably resulted in a lower bulk density in the older cultivated fields. On the other hand, there was no effect of time in the rocky P soil, whose bulk density remained very similar irrespective of the length of time it had been under sugar cane cultivation. The presence of rocks in the profile of the P soil was the probable cause for this unchanged situation, as only mild loosening work was possible to alleviate compaction under such conditions.

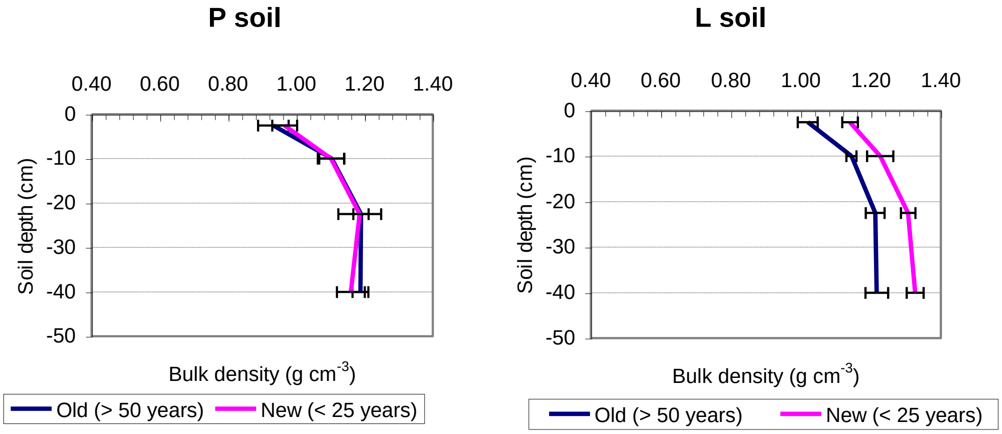


Figure 7.14 Effects of length of time under manual sugar cane cropping on bulk density of the two major soil groups in the sub-humid zone of Mauritius

7.3.4.3 Bulk density and length of time during which mechanized practices have been adopted

The bulk density of the P soil was not significantly affected, whether mechanized practices had been adopted in the long-term or only recently (Figure 7.15). However, the trend was for the subsoil to be more compact with time. This lack of significant effect on bulk density is similar to what was noted when fields under long-term cropping were compared to those under recent cropping. It therefore appears that the effects of cropping or mechanization on bulk density expressed themselves at an early stage in the P soil and an equilibrium had been rapidly reached, so that bulk density no longer changed significantly with time.

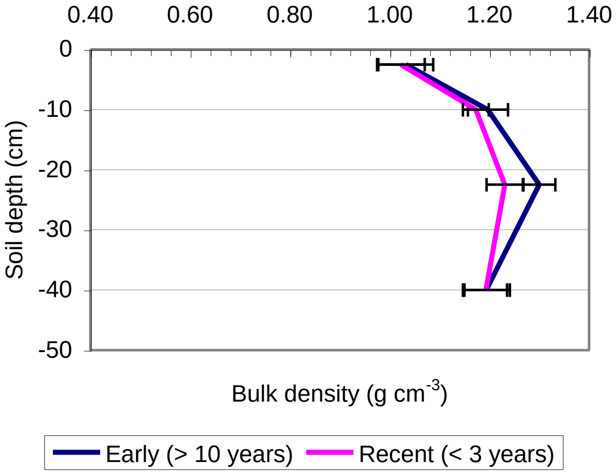


Figure 7.15 Effects of length of time for which mechanized practices have been implemented on bulk density of P soil of Mauritius cropped with sugar cane

7.3.5 Plant available water

7.3.5.1 Effects of manual and mechanized sugar cane cropping practices on plant available water

Under native vegetation, the plant available water (PAW) of the soils of Mauritius varied between 40 and 60 mm for the top 50 cm layer (Figure 7.16). The highest values were found in the rock-free L and F soils, where some 55 mm of water were available, compared to about 45 mm for the rocky P and B soils and the rock-free H soil.

The effects of sugar cane cropping on PAW were variable. Thus, PAW values were significantly higher when P soil was cropped by sugar cane than when under native vegetation, were similar in the L and B soils, and were significantly lower in the F and H soils. The adoption of mechanized practices either had no significant effect, as in the B, F and L soils, or led to an increase in PAW as in the P and H soils.

Klute (1986) has reviewed factors affecting water retention, this parameter being dependent on two major soil properties, namely texture or particle-size distribution of the soil, and structure or arrangement of the particles. Organic matter has also been identified as playing a role in determining PAW, either directly through its hydrophylic nature, or indirectly as a result of structure modification. In Mauritius, there was another factor that needed to be considered, namely the rock content of the soil. Thus, upon derocking and land preparation prior to cropping, a higher volume of soil material became available within the profile. It is therefore not surprising that the P soil had a higher PAW when cropped with sugar cane than when it was under native vegetation. In the case of the F and H soils, where no derocking has taken place, the decrease in PAW associated with sugar cane cropping could be ascribed to the decline in aggregate size and lower SOM content in the top layers (Figures 7.7 and 5.1).

As expected, there was a further increase in PAW in the P soil when mechanized treatment was adopted, given that further derocking had been undertaken prior to the introduction of

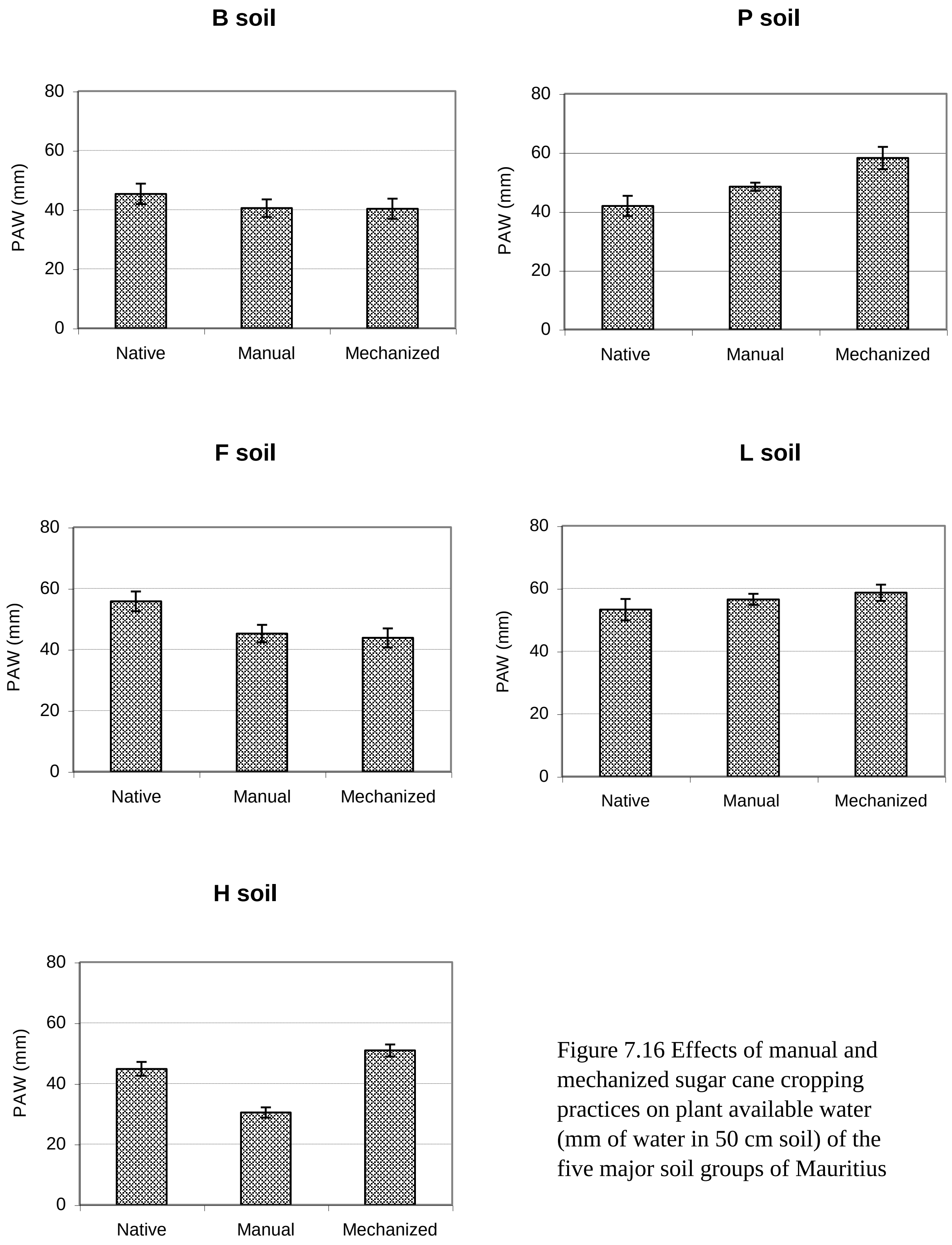


Figure 7.16 Effects of manual and mechanized sugar cane cropping practices on plant available water (mm of water in 50 cm soil) of the five major soil groups of Mauritius

mechanized harvesters. The fact that PAW also increased in the H soil with the adoption of mechanized practices could be ascribed to the higher bulk density upon the soil compaction introduced by mechanization. The effect of compaction on a soil is to decrease its total porosity, particularly the volume of the existing large inter-aggregate pores (Hillel, 1980). On the other hand, the total volume of intermediate size pores would tend to increase in a compact soil since some of the originally large pores have been squeezed down to this size by compaction, while the intra-aggregate pores remain unaffected. The net effect would therefore be to increase the total volume of pores that retain water at the expense of those that conduct water, hence the higher PAW under mechanized conditions.

7.3.5.2 Plant available water and length of time during which sugar cane has been cropped manually

The trend was for recently cultivated fields to have a higher PAW than those that have been under cultivation for a longer period (Figure 7.17). However, this PAW decrease with time was significant only in the rock free L soil. This difference could again be explained by the fact that a higher bulk density in the newly cultivated L soil led to a higher volume of water-retaining pores (Figure 7.14). Similarly, the lack of effect on bulk density explains why PAW remained unchanged in the P soil.

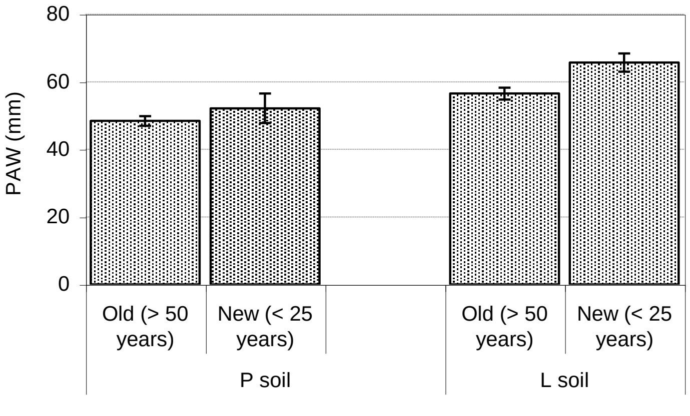


Figure 7.17 Effects of length of time under manual sugar cane cropping on plant available water (mm of water in 50 cm soil) of the two major soil groups in the sub-humid zone of Mauritius

7.3.5.3 Plant available water and length of time during which mechanized practices have been adopted

The PAW of the P soil was lowered when mechanized practices have been adopted over a long period (Figure 7.18). Compaction was not the reason for the decrease in PAW. In this case, the recently mechanized fields had much higher clay contents than the fields where mechanized operations had been adopted earlier. The reverse was however true for aggregate size. In fact, the most plausible explanation for the much higher PAW of the recently mechanized fields lay in their much higher SOM content, as a result of the practice of applying large amounts of organic matter, particularly compost, when fields had undergone extensive land preparation for mechanization.

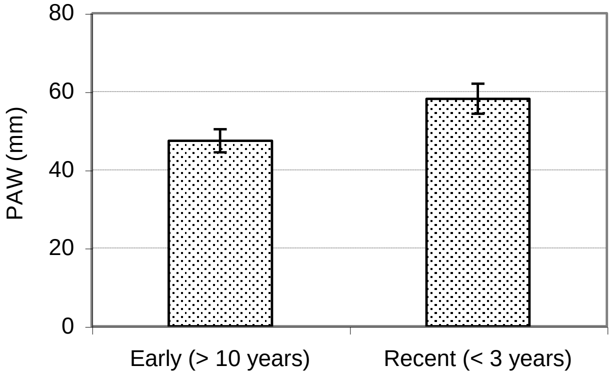


Figure 7.18 Effects of length of time for which mechanized practices have been implemented on plant available water (mm of water in 50 cm soil) of P soil of Mauritius cropped with sugar cane

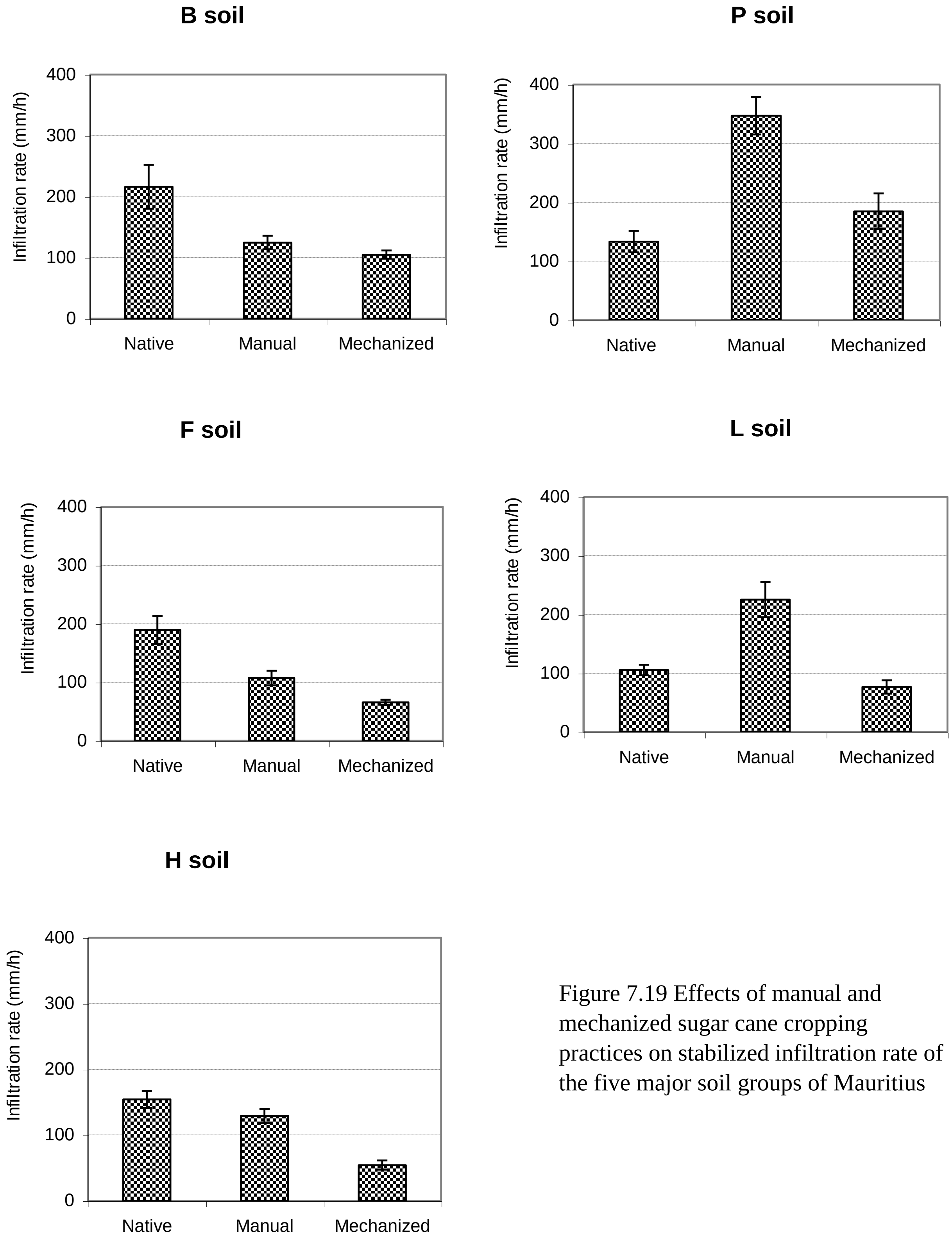
7.3.6 Stabilized infiltration rate

7.3.6.1 Effects of manual and mechanized sugar cane cropping practices on stabilized infiltration rate

In general, the stabilized infiltration rate of the soils was relatively high under native vegetation, exceeding 100 mm h^{-1} in all of them (Figure 7.19). The infiltration rates in the sub-humid L and P soils were actually lower than that of the humid H soil, while the super-humid F and B soils were the most permeable.

With sugar cane cropping, the stabilized infiltration rate of the sub-humid L and P soils increased significantly to more than double their original value. On the other hand, the rate for the cultivated soils from the humid and super-humid zones, i.e. the H, F and B soils, were significantly lower than those of the virgin soil. Finally, there was no ambiguity concerning the effects of mechanized practices on the infiltration rates of the soils: there was a significant decrease in stabilized infiltration rate in all five soils when shifting from manual to mechanized conditions.

As noted by Hartemink (1998b), it was not the presence of sugar cane which had a direct effect on infiltration rate, but rather the traffic associated with the crop, particularly the mechanized cultural operations, such as fertilizer and herbicide applications. If such operations were conducted under wet soil conditions, various phenomena such as compaction, surface crusting and other forms of physical deterioration were liable to happen and impact negatively on stabilized infiltration rate. The decrease in infiltration rate that was associated with sugar cane cropping in Mauritius was found only in soils in the humid and super-humid zones, where cultural operations were frequently undertaken under wet conditions. In contrast, there was no such decreasing effect in the two soils of the sub-humid zone, which were subjected to traffic under drier conditions and in fact, sugar cane cropping actually increased stabilized infiltration rate in these two soils. A possible cause for this increase was that there were more roots and associated soil macro-fauna in the sugar cane



B soil

P soil

F soil

L soil

H soil

Figure 7.19 Effects of manual and mechanized sugar cane cropping practices on stabilized infiltration rate of the five major soil groups of Mauritius cultivated soils thanks to the input of irrigation, giving rise to more numerous large inter-aggregate pores, as shown by the decrease in bulk density in the topsoil of the L and P soils caused by sugar cane cropping. This increased macro-porosity was obviously favourable to surface infiltration of water, since the largest pores were the most conductive as demonstrated by Poiseuille's law (Hillel, 1980).

On the other hand, the traffic associated with harvesting had already been shown to lead to topsoil compaction in all soil groups because of the high axle loads of both harvesters and in-field cane bins. In this case, the total porosity was reduced when a proportion of the existing macro-pores was converted to micro-pores under the compressing forces. As the stabilized infiltration rate depends on the number of macro-pores in the soil, the topsoil compaction was bound to reduce its water intake capacity. Thus, the decrease in infiltration rate with mechanized harvest in all soils was related to the increase in bulk density within the topsoil, particularly in the 0 – 5 cm layer.

7.3.6.2 Stabilized infiltration rate and length of time during which sugar cane has been cropped manually

Fields that had been cultivated for a longer period had a higher stabilized infiltration rate than fields recently planted with sugar cane (Figure 7.20). However, while the increase in infiltration rate was not significant in the rocky P soil, the difference was large enough to be significant in the rock-free L soil. In both cases, the stabilized infiltration rate of the recently cultivated fields was also higher than that of the virgin fields. There has thus been a gradual improvement in this parameter from the moment sugar cane was introduced. This positive effect of cultivation on infiltration rate was probably induced by the build-up with time of macro-pores from roots and activities of the soil meso- and macro-fauna, such as earthworms. In the L soil, it could also be related to the decrease in bulk density that occurred when sugar cane had been cultivated for a longer period.

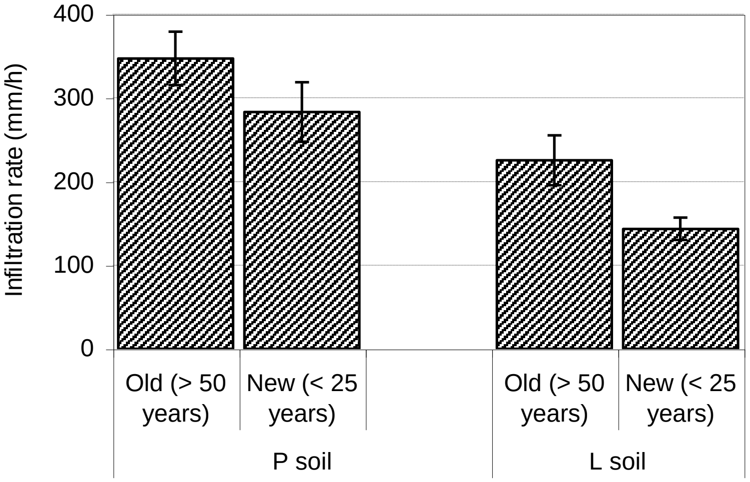


Figure 7.20 Effects of length of time under manual sugar cane cropping on stabilized infiltration rate of the two major soil groups in the sub-humid zone of Mauritius

7.3.6.3 Stabilized infiltration rate and length of time during which mechanized practices have been adopted

The duration of P soil exposure to mechanized practices had no effect on its stabilized infiltration rate (Figure 7.21). It is likely that any change in macro-porosity would have actually taken place in the first years of implementation of mechanized practices, with no further effect in subsequent years. This observation was again supported by the observation that bulk density in the mechanized treatments had not been affected with time.

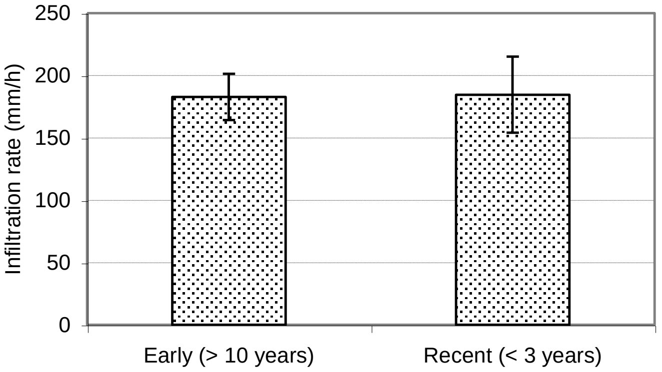


Figure 7.21 Effects of length of time for which mechanized practices have been implemented on stabilized infiltration rate of P soil of Mauritius cropped with sugar cane

7.4 Conclusion

As opposed to what has been observed in other sugar cane producing countries, the major soil groups of Mauritius were not very susceptible to change as a result of sugar cane cropping or following the introduction of mechanized practices. Changes occurring in the soil physical quality parameters investigated were in general relatively small and variable and could sometimes be related to the climatic zone in which the soils were found, or to their rock content. The effects of cultivating sugar cane might occasionally be detrimental to the physical properties of the soil, as generally observed in the literature, but beneficial effects were also found, even though it could not be said that the positive effects outweighed the negative ones. The only case where a totally significant negative impact has been demonstrated occurred with respect to the stabilized infiltration rate of water when mechanized practices were introduced.

As to the effects of time under cultivation on soil physical quality, the results indicated that there was hardly any regular evolution with time for most parameters. In most cases, there was either no effect or only small and variable changes, indicating that the soil reached an equilibrium rapidly once the native vegetation has been replaced by sugar cane. Similarly, the impact of mechanization was much more obvious in the short-term than in the long-term. If there was any effect of mechanization on soil physical properties, such an effect was observed right from the onset.

CHAPTER 8

SUMMARY AND RECOMMENDATIONS

8.1 Summary

8.1.1 Purpose of the study

Though the sugar industry in Mauritius contributes only 3.5% to the national GDP, it is an important component of the national economy as sugar exports represent some 19% of total foreign exchange earnings. Sugar is by far the most important agricultural product of Mauritius and sugar cane covers some 40% of the island or about 85% of the total cultivated area. The sugar industry directly employs about 4% of the total manpower of the island and sugar cane remains a source of revenue to some 28 000 small planters owning less than 10 ha.

Comparative studies elsewhere in South Africa, Australia, or Papua New Guinea, have shown that sugar cane cropping leads to soil degradation. As a result, there is an apprehension that it would no longer be possible to produce sugar cane in a sustainable manner if current production practices are maintained. A preliminary study undertaken in the 1970's has in fact shown that soil degradation occurred in Mauritius with sugar cane cropping. If there has been further degradation of the soil since that study was carried out, then the long-term sustainability of the sugar industry will be threatened. Furthermore, the industry has to adapt to a more competitive international environment, which entails the rapid replacement of manual practices by mechanized ones. These new mechanized practices, which include land preparation and leveling, rock removal, and mechanized harvest, could further exacerbate soil degradation.

In the light of the above statements, it is therefore essential to ascertain whether sugar cane cropping and the adoption of mechanized practices have had negative effects on soil quality.

Recommendations can then be formulated to maintain or restore soil quality, and future research avenues identified.

8.1.2 Results evolved from study

This study was implemented to determine the effects of sugar cane cropping, and the adoption of mechanized practices after land preparation, on soil quality in Mauritius. In addition, the effects of length of time under sugar cane cropping and following implementation of mechanized practices were assessed. To determine the effects of cropping, pristine soils were used in comparison with sugar cane soils cultivated in a conventional manner. The latter were then compared to soils where land preparation and mechanized practices had been implemented to assess the effects of adopting mechanized practices. For temporal effects, old cane soils (> 50 years) were compared to new cane soils (< 25 years) and early mechanized soils (> 10 years) were compared to recently mechanized soils (< 3 years). Biological, chemical and physical soil quality parameters were measured in the course of the study. The biological quality parameters were soil organic matter and microbial biomass, while the chemical ones included pH, cation exchange capacity, exchangeable bases and base saturation. The physical parameters studied were particle size distribution, aggregate size distribution and stability to water, bulk density, plant available water and stabilized water infiltration rate. The main results evolved from the study are summarized below.

1. Cropping with sugar cane is shown to have had both positive and negative effects on the quality of the major soils of Mauritius. These effects were associated with the cultural practices that were adopted in the crop production process. In some instances, cultural practices differed because of differences in climate, and these have produced contrasting effects on soil quality. The cultural practices that have had the greatest effects on soil quality were identified as tillage, organic amendments, fertilization, and trash management after harvest.

2. Topsoil OM generally decreased with cropping. The probable cause was soil tillage, which exposed the SOM to accelerated decomposition. However, tillage also produced mixing of topsoil with subsoil, resulting in enhanced OM in the subsoil. In addition, topsoil microbial biomass declined with sugar cane cropping as there was less material available for decomposition. The downward transfer of OM had a positive effect in the subsoil by increasing the stability of its aggregates.

3. Soil pH, exchangeable bases and base saturation generally improved with sugar cane cropping due mainly to the organic amendments that were added to the soil at planting and just after harvesting. Soil acidification was also observed in one instance, probably as a result of the application of nitrogenous fertilizers. On the other hand, the higher plant biomass produced by fertilization meant that more OM, mainly in the form of plant roots and trash, was returned to the soil, thereby enhancing SOM content. The management of trash at harvest played an important role in the evolution of soil quality. Burning of trash before harvest lowered the return of carbonaceous material to the soil, whereas trash conservation under green cane harvesting had a positive effect through an improved return of OM to the soil.

4. The adoption of mechanized practices had relatively little effect on the chemical quality of the major soils of Mauritius, as soil pH, CEC, exchangeable cation content and base saturation were mostly unaffected. This was not surprising as soil disturbance for land preparation and rock removal was the major activity in the implementation of mechanized practices and was not expected to impact on the soil’s chemistry. There was more soil disturbance under humid to dry conditions than under very wet conditions. SOM consequently decreased with the adoption of mechanized practices in the dry zones. In one soil where chemical quality was affected by mechanization, the changes were positive and could be ascribed to the large amounts of organic amendments that had been added to the soil after land preparation and rock removal. As expected, the adoption of mechanized practices had a greater influence on soil physical properties. Compaction invariably occurred in the topsoil and can be

directly related to traffic associated with mechanized harvesting. Compaction also led to a reduced water infiltration rate as a result of the reduction in topsoil macro-porosity, and to an increase in plant available water.

5. No clear conclusion could be drawn regarding the effect of time under sugar cane cropping on the quality of the sub-humid soils of Mauritius. Soil properties were not systematically aggraded or degraded under long-term cultivation and changes were mainly small and variable.

6. Soil quality declined with time after the adoption of mechanized practices. This decline resulted from the policy of adding large amounts of amendments to the soil when mechanized practices were implemented, and allowing the built-up SOM and nutrients present to be depleted with time. In physical terms, the impact of adopting mechanized practices was observed right from the onset and did not evolve with time.

To sum up, sugar cane cropping had variable effects on soil quality in Mauritius. Negative effects were mainly confined to the topsoil in the instances where soil degradation was observed. The biological quality of the topsoil decreased with cropping as OM and microbial biomass declined whereas chemical quality generally improved with higher pH and exchangeable base content. On the other hand, topsoil physical quality decreased following the adoption of mechanized practices, through the compacting effect of heavy agricultural machinery traffic which also reduced the water intake rate. The quality of the soil was not systematically affected by the length of time during which it has been cropped, but it did decline with time after the adoption of mechanized practices.

8.2 Implications and recommendations for the sugar industry of Mauritius

8.2.1 Application of research results

From the agronomic viewpoint, the OM depletion in the topsoil with cropping of sugar cane will impact negatively on the long-term yield. A direct consequence of this depletion is the reduction in soil N content (Sumner, 1997) as N is released through mineralization by soil micro-organisms into inorganic forms which are available to the sugar cane. This process supplies a significant portion of the N needs of the crop, as studies have shown that 85% of the N in sugar cane is derived from the N mineralized in the soil (Ng Kee Kwong *et al.*, 1983). As total N content and soil microbial biomass generally decreased with sugar cane cropping, N mineralization and availability will also decrease. The organic pool will thus provide less N to the sugar cane crop, and more fertilizer N will be needed to maintain crop productivity. The OM depletion in the topsoil is also expected to have negative consequences for the sustainability of the sugar industry by rendering the soils more susceptible to erosion. An OC value of 2% has been quoted as the threshold below which the soil can be considered erodible (Morgan, 1986). The OC content of the major soils of Mauritius is still above this threshold value under sugar cane cropping, but the L soil could be at risk since its OC content is close to this threshold, making it the soil most susceptible to erosion in Mauritius (Seeruttun, 2006).

To ensure that the topsoil OM level does not decrease any further under cropped conditions, trash retention through green cane trash blanketing, addition of large amounts of organic wastes and green manuring should be favoured. Trash delivers only negligible amount of N to the next sugar cane crop, but contributes significantly to raising the OM level of the soil (Ng Kee Kwong *et al.*, 1987). In fact, the N liberated from the trash is mainly immobilized in the soil, reflecting that it is an N source of slow availability to the crop (Basanta *et al.*, 2003). For trash to be retained, the sugar cane must be harvested green, leaving a trash blanket on the soil surface. However, as trash blanketing affects soil water and temperature, its implementation should be restricted to the sub-humid and humid zones since the mulch lowers soil temperature by 1 to 2°C and reduces yield in the super-humid zone (Seeruttun *et al*., 1998). On the other hand, the mulching effect conserves soil water by reducing evaporation and has been shown to lead to a higher sugar cane yield in the sub-humid zone (Mc Intyre *et al*., 1996).

Application of organic waste to sugar cane fields is already a common practice in Mauritius. The main organic waste is filter mud, but its application rates vary depending on the producers. Poultry litter is another possible form of organic waste that could be used. It is as effective as mineral fertilizers in increasing sugar cane yields and has the added advantage of improving the nutrient status of the soil (MSIRI, 2006). A third possible source of organic waste is stillage slop, a waste product from the fermentation process when molasses are converted to ethanol. According to the multi-annual adaptation strategy for the sugar industry of Mauritius for the years 2008 to 2013 (Government of Mauritius, 2006), 30 million l of ethanol will be produced when this strategic plan is fully implemented. As 13 l of slop are produced for every l ethanol (Paturau, 1989), some 390 million l of stillage slop would become available, part of which could be applied to sugar cane fields in a concentrated form known as condensed molasses solubles or CMS. Applications of slop at a rate of 80 m^3 ha^{-1} $year^{-1}$ have been shown to lead to an accumulation of OM in the soil in the long-term with a strongly positive N balance, while increasing pH and exchangeable bases and decreasing exchangeable Al levels (de Resende *et al*., 2006). On the other hand, the multi-annual adaptation strategic plan from 2008 to 2013 promotes sugar mill centralization and the concurrent adoption of more efficient milling technologies such as the use of diffusers. As no filter mud is produced with this technology, the main source of organic waste of the sugar cane fields will disappear and alternative sources need to be found. One definite possibility is to use sewage sludge, a ready and constant source of organic waste. Its application to agricultural land represents the most sensible economic option for its disposal (Beck *et al*., 1995), the more so as trials have shown that sewage sludge in Mauritius has extremely low levels of main organic pollutants (Soobadar *et al*., 2004) and its application to the soil carries little risk of contaminating groundwater by heavy metals (Toory *et al*., 2004). Furthermore, it has been shown that application of composted sewage sludge did not increase Mn, Cu, Fe, or

Zn concentrations in sugar cane leaf tissue beyond acceptable limits (Viator *et al*., 2002). The main obstacle to its use in sugar cane fields could be a certain reticence from farmers, considering the source of this organic waste product.

The incorporation of a rotation break in the sugar cane monoculture holds considerable scope for improving its biological status (Pankhurst *et al*., 2003). In addition to increasing SOM content, these green manures enhance sugar cane yield. In this respect, a well-managed single rotation crop of soybeans or peanuts has been shown to contribute substantial amounts of fixed N into the soil, to increase sugar cane yields and to impact on soil health (Garside and Bell, 2001). Trials in Mauritius have shown that higher yields are indeed obtained when legume green manure crops are incorporated into the soil and that lablab (variety *Rongai*) was the best species, fixing between 170 and 200 kg N ha^{-1} from the atmosphere (MSIRI, 2005). However, as the experience from Garside *et al*. (2004) has shown, the amount of green manure produced is highly dependent on a good input of water for growth. To reap the highest benefit from this practice, the green manure must therefore either be planted during the wet season under rainfed conditions or be regularly irrigated. As the growing season of lablab lasts some three months, that much time will have elapsed between the last sugar cane harvest and the replanting of the next crop. Thus, if green manuring is adopted under short season planting, the previous crop must be harvested early to allow time for the legume to grow under irrigated conditions, before ploughing in and replanting. Alternatively, under rainfed conditions, the legume should be planted in the wet season and the next sugar cane crop planted in the long season.

The soil physical degradation in the form of compaction that results from the adoption of mechanized practices appears inevitable. Compaction is an unavoidable consequence of mechanized agriculture and should therefore be considered as a factor of the crop production system (Torres and Rodriguez, 1996). It has detrimental effects on sugar cane yield, Swinford and Meyer (1985) having shown that yield was negatively correlated with bulk density values. The consequence of compaction on the environment is a lower infiltration rate, increased runoff, higher risk of soil erosion, greater loss of agrochemicals and therefore more pollution. While mechanization of cultural practices must be implemented for economic reasons, strategies need to be developed to alleviate its drawbacks.

Inter-row decompaction in ratoons is an option for eliminating compaction. Torres and Pantoja (2005) showed that one pass of a double-shank subsoiler was sufficient to restore soil physical properties in ratoons while Swinford and Boevey (1984) observed increases in cane yield following ripping of the inter-row in machine-compacted plots. However, this practice cannot be contemplated for Mauritius since the decompacting implements cannot be operated properly in the presence of trash. In the management of compaction, prevention is therefore the best strategy. To minimize, offset or eliminate compaction, Torres and Rodriguez (1996) have recommended that vehicles be kept off the fields when soil conditions were too wet, tyres be run at lowest possible inflation pressure, field operations be combined to reduce traffic, row spacing be matched to machine tracks (or vice-versa) and controlled traffic paths be implemented. Braunack (2004) also recommended that the number of passes by fully laden haulouts be reduced in mechanized harvesting, and that super single tyres be used rather than dual ones. In addition, Braunack (2004) suggested that lowering the pressure in the tyres might provide an additional benefit in reducing compaction, but at the expense of tyre life. Of these measures, in-field trailers fitted with low-pressure tyres have already been recommended for use in the super-humid zone of Mauritius (MSIRI, 2000). Unfortunately, the imperatives of industrial production have also meant that mechanized operations are often undertaken under wet conditions and this trend could even be accentuated with mill centralization. Other possible measures, particularly controlled traffic, seem promising but need to be tested prior to implementation.

8.2.2 Suggestions for future research

The most pertinent soil quality parameters to emerge from this study are OM, pH, bulk density and water infiltration rate. The evolution of the OM was the main indicator of the soil's biological quality. On the other hand, measurements of microbial biomass were less important since there was a general correlation between microbial biomass and topsoil OM, and the latter parameter gave a clear indication of the evolution of the microbial population. A similar reasoning could be applied to CEC, a chemical quality parameter that is highly dependent on OM. The evolution of the soil's chemical quality is best monitored through pH, as its evolution influences micro-organism activity and availability of plant nutrients, rather than through changes in exchangeable base status and base saturation. As far as physical quality is concerned, the indicators of compaction (bulk density) and water movement (infiltration rate) were more pertinent than the indicators of texture (particle size distribution), structure (aggregate size distribution and stability) or water retention (plant available water).

An additional soil quality parameter that deserves investigation in the short-term is the labile C within the total OM pool, since it is the most labile pool that is the key determinant of soil properties (Moody *et al*., 1999). Under sugar cane, key soil properties such as CEC, aggregate stability and microbial biomass are more strongly related to the labile C fraction than to total organic C *per se*. Total C measures both labile C and the inert charcoal fraction of the SOM, and is therefore not a sensitive indicator of changes in labile C (Moody *et al*., 1999). Research on regeneration of OM in sugar cane soils should therefore include the determination of the labile C pool.

There are different possibilities for regenerating SOM. It has already been mentioned that one possible source of OM is the legume fallow. Experimental work in Mauritius on legume green manure crops has shown that lablab was a more effective N fixer than cowpea, soybean and crotalaria, and has provided conclusive evidence that incorporation of these crops into the soil prior to replanting sugar cane can significantly increase yield (MSIRI, 2006). However, additional work needs to be done to determine whether the positive effects of incorporating a leguminous crop between two crop cycles has long lasting effects on the OM and aggregation status of the soil. In addition, only about 25% of the N fixed by the legume is absorbed by the ensuing sugar cane crop. The fate of the remaining fixed N needs to be investigated in subsequent ratoons to verify whether it becomes available to the crop at a later stage.

Experimentation at MSIRI using sewage sludge has shown conclusively that there is no risk to public health if this waste is applied to sugar cane fields. However, the use of sewage sludge also requires the simultaneous application of chemical fertilizers to avoid loss in cane production (MSIRI, 2004). There is scope for work to determine the correct dose of this product for building up the organic C status of the soil in conjunction with optimum N fertilizer application.

With respect to trash management, it has been shown that most cane trash decomposes within a year after harvest (Robertson and Thorburn, 2007a). However, decomposition rate was partially dependent on temperature and rainfall, among other factors. This indicates that there are possible differences in the rate of trash decomposition between the soils of the sub-humid zone and those of the super-humid zone, and their relative effects on soil quality should be investigated. Furthermore, Robertson and Thorburn (2007b) have suggested that some 10 to 20% reductions in N fertilizer applications might be possible after 15 to 25 years of trash blanketing, provided that crop yields and N losses to the environment under trash blanketing were similar to those under the burnt system. The quality of the soils that have been long enough under trash blanketing of Mauritius needs to be investigated to verify this assertion, which if proven, will impact positively on production costs.

As far as managing soil compaction is concerned, controlled traffic is a system that could help maintain a zone better adapted for sugar cane growth by restricting soil compaction to inter-row traffic lanes (Braunack *et al*., 1995), leaving a loose rooting zone in the cane row. McGarry *et al*. (1997) have shown that, after five ratoons, soil in the row was less dense and had better porosity than soil in the inter-row which had become a hard traffic zone with potential for increased traction and improved wet-weather access. However, the benefits of controlled traffic cannot be fully realized in Mauritius, as in Australia, unless the current mismatch between row spacing (1.5 to 1.6 m) and equipment track width (1.8 m) is eliminated (Braunack and McGarry, 2006). The effects of controlled traffic on row and inter-row bulk density and water infiltration rate should be investigated, particularly in relation to efforts for adapting row spacing to equipment track width.

Even though it is not deemed to alleviate compaction, reduced or minimum tillage can lead to substantial cost savings with environmental benefits without yield penalty if it is adopted in conjunction with row spacings that match harvester and in-field transport wheel spacings (Bell *et al*., 2001). Work on minimum tillage practice in Mauritius needs to be revisited, as recommendations for its adoption were based essentially on trials using manual harvesting practices, which led to little change in soil physical properties (McIntyre and Barbe, 1990). Trials combining controlled traffic and minimum tillage strategies need to be undertaken as a means for minimizing soil degradation and maintaining productivity in the long-term, as suggested by Braunack and McGarry (2006).

In the long-term, research will have to focus on the changes in soil quality as new farming systems are adopted. Braunack and McGarry (2006) have suggested that the combination of controlled and reduced traffic could form the basis of a farming system to protect the soil resource and maintain long-term productivity in Australia. Similarly, the combination of raised beds, dual row planting, minimum tillage, controlled traffic and legume fallows in the sugar cane farming system has already been touted as a means of improving profitability, sustainability and environmental responsibility (Garside *et al*., 2004). The perceived advantages of this new system are that it replaces inorganic nitrogen fertilizer in the plant crop, improves soil health, reduces compaction in the cultivated area, and virtually eliminates offsite movement of soil, fertilizer and chemicals (Milford, 2005). Dual row planting has already been shown to give higher yields in Mauritius (MSIRI, 2006), with the additional benefit of a considerable improvement in harvester efficiency, while minimum tillage has long been recommended on sloping lands as a soil conservation measure (McIntyre *et al*., 1984). However, the proponents of this new farming system have tended to focus essentially on biomass production and on the economic aspects of the system (Garside *et al*., 2004). The effects of integrating all these different practices on soil quality remain unknown because they have not been adopted long enough whereby their impact on soil quality can be stressed. If the sugar industry of Mauritius follows the same trend as in Australia, this new farming system needs to be tested locally, while including into it an aspect that is specific to Mauritius, which is the removal of stones from the permanent beds using either a stone aligner or a stone crusher. To conclude, it is foreseeable that cultural practices will change as the sugar industry of Mauritius adapts to its new economic environment, but the effects of these changes on soil quality must be determined to ensure that the new systems adopted are agronomically viable and environmentally sustainable.

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APPENDIX 1

Appendix 1.1 Average values and standard errors of particle size distribution of five major soil groups of Mauritius as affected by sugar cane cropping and mechanized practices

B soil

		Treatment		
Layer (cm)	Particle size	Virgin	Manual	Mechanized
0 - 5	Sand	42.7±1.9	29.2±2.0	20.6±1.5
	Silt	27.1±1.6	25.9±0.7	27.3±0.6
	Clay	30.2±1.7	44.9±1.7	52.1±1.1
5 - 15	Sand	42.9±1.5	27.2±1.9	19.9±1.5
	Silt	28.7±1.6	25.5±0.7	27.4±0.5
	Clay	28.4±2.1	47.3±1.9	52.7±1.1
15 - 30	Sand	42.7±1.9	24.0±2.1	19.6±1.9
	Silt	29.9±1.8	25.1±0.6	24.8±0.5
	Clay	27.4±2.6	51.0±2.3	55.6±1.7
30 - 50	Sand	43.3±2.0	28.9±2.1	25.1±3.3
	Silt	29.5±1.7	26.4±0.9	23.3±0.9
	Clay	27.3±2.3	44.7±2.1	51.6±3.9
0 - 50	Sand	43.0±1.8	27.1±1.4	22.0±2.2
	Silt	29.2±1.6	25.8±0.5	25.0±0.4
	Clay	27.8±2.2	47.1±1.7	53.1±2.2

P soil

		Treatment		
Layer (cm)	Particle size	Virgin	Manual	Mechanized
0 - 5	Sand	21.5±1.4	29.0±2.8	20.6±1.5
	Silt	19.6±0.8	18.0±2.3	21.7±1.9
	Clay	57.9±1.6	53.1±4.4	57.8±2.8
5 - 15	Sand	22.0±1.8	28.4±2.9	20.0±1.8
	Silt	17.0±0.6	21.1±0.9	20.9±0.5
	Clay	61.0±2.1	50.5±3.3	59.1±2.1
15 - 30	Sand	19.1±2.0	28.2±2.9	19.5±2.2
	Silt	17.5±0.8	21.6±0.8	21.2±0.5
	Clay	63.5±2.4	50.2±3.2	59.3±2.4
30 - 50	Sand	17.6±1.6	30.0±3.6	20.3±3.1
	Silt	18.0±0.7	21.6±0.8	21.7±1.5
	Clay	64.4±2.1	48.4±3.6	58.1±3.8
0 - 50	Sand	19.4±1.6	29.0±3.1	20.0±2.3
	Silt	17.8±0.6	21.2±0.7	21.4±0.9
	Clay	62.9±2.0	49.8±3.3	58.6±2.8

Appendix 1.1 (continued) Average values and standard errors of particle size distribution of five major soil groups of Mauritius as affected by sugar cane cropping and mechanized practices

F soil

		Treatment		
Layer (cm)	Particle size	Virgin	Manual	Mechanized
0 - 5	Sand	28.2±0.6	33.8±1.6	34.4±1.1
	Silt	30.2±0.3	28.9±0.7	31.0±0.6
	Clay	41.6±0.4	37.3±0.9	34.5±0.7
5 - 15	Sand	30.2±0.6	32.5±1.7	32.7±0.9
	Silt	31.2±0.8	29.3±0.6	31.6±0.8
	Clay	38.6±1.1	38.3±1.1	35.7±0.5
15 - 30	Sand	38.6±2.1	34.3±2.3	33.8±1.4
	Silt	27.8±1.4	28.6±0.7	32.9±1.1
	Clay	33.5±1.5	37.0±1.6	33.3±1.5
30 - 50	Sand	51.1±2.1	44.9±2.7	46.3±2.3
	Silt	23.9±1.0	25.2±1.4	28.3±1.5
	Clay	25.0±1.4	29.9±1.8	25.5±1.5
0 - 50	Sand	40.9±1.3	38.1±1.8	38.6±1.3
	Silt	27.2±0.7	27.4±0.7	30.6±0.9
	Clay	32.0±1.2	34.5±1.3	30.8±1.1

L soil

		Treatment		
Layer (cm)	Particle size	Virgin	Manual	Mechanized
0 - 5	Sand	16.7±1.6	15.3±1.3	14.3±1.5
	Silt	15.2±1.2	18.6±1.8	18.6±3.1
	Clay	68.1±2.8	66.5±2.9	67.1±3.7
5 - 15	Sand	14.1±0.9	14.7±1.2	13.3±1.1
	Silt	15.5±1.4	20.3±1.9	19.4±2.0
	Clay	70.3±2.3	65.0±2.6	67.4±2.6
15 - 30	Sand	10.6±0.9	14.1±1.4	12.8±1.1
	Silt	13.9±1.0	20.7±2.0	18.6±2.0
	Clay	75.5±1.7	65.2±2.7	68.7±2.7
30 - 50	Sand	8.5±0.6	12.7±1.7	10.2±1.1
	Silt	12.6±0.5	19.2±1.8	16.7±2.6
	Clay	78.8±1.0	68.1±2.7	73.1±3.0
0 - 50	Sand	11.1±0.6	13.8±1.4	12.0±1.1
	Silt	13.8±0.8	19.8±1.8	18.0±1.7
	Clay	75.1±1.3	66.4±2.6	70.0±2.3

Appendix 1.1 (continued) Average values and standard errors of particle size distribution of five major soil groups of Mauritius as affected by sugar cane cropping and mechanized practices

H soil

		Treatment		
Layer (cm)	Particle size	Virgin	Manual	Mechanized
0 - 5	Sand	16.5±1.5	18.6±1.0	23.9±1.4
	Silt	22.9±0.5	20.8±1.4	31.5±0.9
	Clay	60.6±1.5	60.6±1.2	44.6±2.2
5 - 15	Sand	16.2±1.6	18.1±1.0	23.1±1.4
	Silt	22.4±0.7	20.6±0.3	31.5±0.9
	Clay	61.4±2.2	61.3±1.2	45.5±2.2
15 - 30	Sand	16.4±2.0	16.7±1.0	23.0±1.9
	Silt	20.9±0.5	19.2±0.3	32.5±1.6
	Clay	62.8±2.3	64.1±1.2	44.6±3.3
30 - 50	Sand	16.6±2.5	11.3±0.6	32.8±4.0
	Silt	20.4±0.7	17.1±0.9	30.4±1.6
	Clay	63.0±2.9	71.6±1.3	36.9±5.4
0 - 50	Sand	16.5±2.1	15.0±0.7	27.0±2.5
	Silt	21.2±0.6	18.8±0.4	31.0±1.4
	Clay	62.4±2.5	66.2±0.9	41.7±3.8

Appendix 1.2 Average values and standard errors of particle size distribution of two soil groups of the sub-humid zone of Mauritius as affected by time under sugar cane cropping

		Médine (P soil)		Richeterre (L soil)	
Layer (cm)	Particle size	Old	New	Old	New
0 – 5	Sand	29.0±2.8	19.7±0.9	15.3±1.3	16.7±1.0
	Silt	18.0±2.3	20.2±0.7	18.6±1.8	20.7±1.4
	Clay	53.1±4.4	60.1±1.2	66.5±2.9	62.6±2.0
5 – 15	Sand	28.4±2.9	18.8±1.0	14.7±1.2	17.0±1.2
	Silt	21.1±0.9	19.2±0.7	20.3±1.9	20.9±1.4
	Clay	50.5±3.3	62.0±1.2	65.0±2.6	62.1±2.2
15 – 30	Sand	28.2±2.9	21.1±2.2	14.1±1.4	16.0±1.5
	Silt	21.6±0.8	19.5±0.8	20.7±2.0	20.7±1.4
	Clay	50.2±3.2	59.5±2.4	65.2±2.7	63.3±2.4
30 – 50	Sand	30.0±3.6	22.9±3.9	12.7±1.7	15.0±1.8
	Silt	21.6±0.8	19.9±1.4	19.2±1.8	21.5±1.1
	Clay	48.4±3.6	57.2±4.4	68.1±2.7	63.5±2.4
0 – 50	Sand	29.0±3.1	21.2±2.4	13.8±1.4	15.9±1.4
	Silt	21.2±0.7	19.7±0.9	19.8±1.8	21.1±1.2
	Clay	49.8±3.3	59.1±2.7	66.4±2.6	63.1±2.1

Appendix 1.3 Average values and standard errors of particle size distribution of P soil of Mauritius as affected by time for which mechanized practices have been adopted

		Treatment	
Layer (cm)	Particle size	Old mechanized	New mechanized
0 - 5	Sand	22.8±1.3	20.6±1.5
	Silt	20.7±0.8	21.7±1.9
	Clay	56.4±1.8	57.8±2.8
5 - 15	Sand	23.2±1.7	20.0±1.8
	Silt	20.2±0.6	20.9±0.5
	Clay	56.7±1.9	59.1±2.1
15 - 30	Sand	25.8±2.9	19.5±2.2
	Silt	21.5±1.8	21.2±0.5
	Clay	52.7±3.1	59.3±2.4
30 - 50	Sand	26.4±3.6	20.3±3.1
	Silt	20.4±0.8	21.7±1.5
	Clay	53.2±3.7	58.1±3.8
0 - 50	Sand	25.2±2.7	20.0±2.3
	Silt	20.7±0.9	21.4±0.9
	Clay	54.1±2.9	58.6±2.8