Evaluation of the phosphorus status of sugarcane soils in Mauritius using agronomic and environmental criteria

by

Tesha Mardamootoo

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Supervisor: Professor C. C. Du Preez

Co-supervisor: Dr K. F. Ng Kee Kwong

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DECLARATION

I declare that the dissertation hereby submitted by me for the Masters of Science 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 dissertation in favour of the University of the Free State.

Signature October 2009

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ABSTRACT

Phosphorus input is vital to the maintenance of profitable sugarcane crop production in Mauritius. The intensive use of some 5,000 tonnes of P annually during the past 50 years is believed to have built up the P status of the sugarcane soils, perhaps even to excessive levels. While this accumulation of P is desirable from an agronomic perspective, there is growing concern in Mauritius about its possible effect on surface water quality. In response to that concern, a study was initiated with the following specific objectives:

i. To review the usage of P fertilisers in sugarcane production in Mauritius and assess their resulting impact on the P status of the main soil groups under sugarcane.
ii. To enlarge the scope of the current method used (0.1M H_2SO_4 extraction) for agronomic P testing so that it also indicates environmental status of sugarcane soils in Mauritius.
iii. To determine the environmental threshold P in soils above which the P will represent a hazard to surface waters.

The five yearly averages of fertiliser P usage by the Mauritian sugarcane industry showed that from the 790 tonnes of P_2O_5 (mainly as rock/guano phosphates) consumed at the beginning of the 20th century, P usage attained a peak of 5,675 tonnes in the 1970s before declining thereafter as a result of a decreasing land area under sugarcane. During the period 2005 to 2008, an average of 3,350 tonnes of P_2O_5 mainly as ammonium phosphates were applied annually to sugarcane which is cultivated in Mauritius mainly on five soil groups, namely the Low Humic Latosol (*Humic Nitosol*)*, the Humic Latosol (*Humic Nitosol*)*, the Humic Ferruginuous Latosol (*Humic Acrisol*)*, the Latosolic Reddish Prairie (*Eutric Cambisol)** and the Latosolic Brown Forest (*Dystric Cambisol*)*.

A method based on 0.1M H_2SO_4 as extractant is currently used as a routine soil test to assess P available to sugarcane in the soils of Mauritius. On the basis of soil P test values, four soil P fertility classes could be discerned, namely:

** Soil group as per FAO classification.*

Fertility class	Soil test P range *0.1M H_2SO_4-P (mg kg^{-1})*	Fertility class description
I	P < 80	Deficient to adequate
II	80 ≤ P < 100	Optimum
III	100 ≤ P < 150	Excessive to highly excessive
IV	P ≥ 150	Highly excessive

Examination of the soil test P data obtained in 1997/1998 showed that 48% of the land still required P fertilisation while approximately 40% had an excess of P (P ≥ 100 mg kg^{-1}). Less than 10% of the soils had an optimum soil P (80 ≤ P < 100 mg kg^{-1}). Moreover, soils with a highly excessive soil P status (P ≥ 150 mg kg^{-1}) rose from 23% in 1997/1998 to 34% in 2005/2006 indicating that with the current P management practice in sugarcane, the P status of soils in Mauritius will shift more and more towards an excess of P.

In spite of the extensive information available on the soil P status, its significance from the freshwater protection angle was, prior to this study unknown due mainly to a lack of a suitable environmental soil P test method. From this perspective, as a laboratory extraction of soil with 0.01M $CaCl_2$ gives a very reliable representation of the P in runoff, the P extractable in a 0.01M $CaCl_2$ (0.01M $CaCl_2$-P) solution was determined in 112 soil samples representing the five main soil groups under sugarcane. The soil samples whose characteristics of pH, organic matter content, exchangeable bases and cation exchange capacity were also determined, were selected to cover a range of 10 to 250 mg kg^{-1} P extractable by the 0.1M H_2SO_4 used for agronomic soil P testing in Mauritius. As the environmental soil test P must be independent of soil properties and the concept of degree of P saturation (DPS) meets that criteria, the ammonium oxalate DPS (DPS_{ox}) was determined in the 112 soil samples to provide a reliable pointer of P susceptibility to loss from soils. Since it is very unlikely that ammonium oxalate extraction would be used as a routine soil test, the relationship between DPS_{ox} and 0.1M H_2SO_4-P was established by conventional statistical regression techniques.

The results obtained indicate that no single soil characteristic could be said to have a distinct influence on the amount of P extracted by either the 0.1M H_2SO_4 or the 0.01M

$CaCl_2$ or by the DPS_{ox}. Indeed the correlation (r^2) between the 0.1M H_2SO_4-P, 0.01M $CaCl_2$-P, DPS_{ox} with the individual measured soil characteristics was low and never exceeded 0.28 in the case of 0.1M H_2SO_4-P and 0.52 with 0.01M $CaCl_2$-P. The DPS_{ox} exhibited the poorest relationship with the soil properties with none of the r^2 values being above 0.16. Instead the low r^2 values observed indicated as confirmed by multiple regression analysis that the amount of P extracted by each reagent would be the result of the combined effects of certain soil characteristics.

The results moreover showed that for soil P not to constitute a hazard to the freshwaters in Mauritius, the DPS_{ox} should not exceed 3.10±0.10% and the 0.01M $CaCl_2$-P must lie below 18±1µg L^{-1}. Moreover the linear fit regression equation 0.1M H_2SO_4-P = 17.3 + 23.2 DPS_{ox} with r^2 = 0.54 was found to most appropriately describe the relationship between 0.1M H_2SO_4-P and DPS_{ox}. From that equation the threshold DPS_{ox} of 3.10±0.10% would correspond to a range of 85 to 95 mg kg^{-1} of 0.1M H_2SO_4-P which is henceforth considered as the threshold range of P in sugarcane soils in Mauritius above which the soil P would become a hazard to freshwater sources. Using this environmental threshold range of soil P values as basis, the soils can be divided into the following four environmental classes namely:

Environmental class	**Soil P test range** *0.1M H_2SO_4-P (mg kg^{-1})*	**Environmental description**
I	P < 85	Sound
II	85 ≤ P < 95	Safe
III	95 ≤ P < 125	Unsafe
IV	P ≥ 125	Unacceptable

Application of the above criteria showed that in 1997/1998, 58% of the soils did not represent any hazard to freshwater quality in Mauritius. As much as 42% of the sugarcane fields in 1997/1998 had from the environmental viewpoint unacceptably high levels of P (P ≥ 95 mg kg^{-1}) in the soils. After one crop cycle in 2005/2006, the number of fields with unacceptably high levels of P (P ≥ 95 mg kg^{-1}) had risen to 53%. The majority (74%) of the sugarcane fields with an environmentally unacceptable P status were located in the Latosolic Reddish Prairie and Latosolic Brown Forest soils.

In extending the scope of the current agronomic soil test P using 0.1M H_2SO_4 as an extractant into an agro-environmental soil P test, this study demonstrated clearly that the agronomic objectives in P management for sugarcane production in Mauritius are incompatible with the environmental aims of protecting the freshwater resources in Mauritius. With the agronomic threshold range of 80 to 100 mg kg^{-1} P overlapping the environmental range of 85 to 95 mg kg^{-1} P, soils in Mauritius that are agronomically suitable for sugarcane cultivation are on contrary unsafe from the environment protection viewpoint and vice versa.

Keywords: *soil testing, degree of P saturation, threshold P range, soil characteristics, 0.1M H_2SO_4 extractable P, 0.01M $CaCl_2$-P, P usage.*

1 Introduction

1.1 Background

Sugarcane is one of the most important field crops in the tropics. According to FAO (2007) sugarcane, which has a potential of giving more than 120 tonnes biomass per hectare, covers an average of about 22.7 million hectares in the world to produce approximately 1.3 billion metric tonnes of cane and 169 million tonnes of sugar. It is grown in not less than 105 countries, including Mauritius where sugarcane is the most important agricultural crop, occupying some 80% of the cultivated area and playing a significant role in its economy. Indeed though sugarcane production contributed less than 3% of the gross domestic product (GDP) it brings into Mauritius not less than 15% of the foreign exchange making this industry the fourth after the manufacturing, tourist and financial service sectors in terms of foreign exchange earners.

In Mauritius sugarcane is exploited not only for the production of sugar as a sweetener but also for electricity generation using bagasse (fibrous residue remaining after the juice has been extracted from the cane stalk) and for ethanol production from the molasses (sugar liquor remaining after the crystallisation process). Thus in 2008, apart from the 452,000 tonnes sugar produced with the 4.53 million tonnes cane harvested from an area of 62,000 hectares, 1.54 million tonnes bagasse residue was produced and used in cogeneration to supply the national grid with 366 GWh of electricity (16% of the country's needs) while from the 145,000 tonnes of molasses 30,000 tonnes of ethanol could have been produced (Anon, 2009).

1.2 Problem statement

As phosphorus (P) is an essential nutrient for crops including sugarcane, P input is vital to the attainment and maintenance of a profitable sugarcane crop production in Mauritius. However on the basis of the known behaviour of P in soils, the intensive use of some 5,000 tonnes of P annually as practised during the past 50 years in Mauritius must have resulted in a general build up of the P status of many sugarcane soils and perhaps to excessive levels. While this accumulation of P may be desirable from an agronomic perspective,

there is growing concern in Mauritius about its possible environmental hazards, particularly in terms of direct effect on surface water quality. Indeed, pollution of freshwaters by P is now recognised worldwide to be a water quality concern because it contributes to eutrophic conditions and in inland fresh water, P is known to be invariably the major limiting nutrient to eutrophication (Westermann, 2005). Only very small amounts of P have to be lost from the soil to create a P concentration in fresh water ecosystems likely to cause environmental deterioration. Therefore, though it is vital that the productive potential of existing suitable sugarcane lands in Mauritius be raised and fully exploited, it must be done to an extent which must be consistent with the need to safeguard the environment.

Advanced or accelerated eutrophication of surface water leads to problems with its use for fisheries, recreation, industry and drinking due to the increased growth of undesirable algae and aquatic weeds and oxygen shortages caused by their senescence and decomposition (Sharpley and Withers, 1994). In addition, plant and animal communities may be directly affected by the changes in water quality. Such changes in water quality may affect the biosphere by altering habitat, food, nutrient supplies and breeding areas. A common long-term effect will therefore be loss of both faunal and floral communities.

To prevent eutrophication, total P should not exceed 0.05 mg L^{-1} in streams entering lakes/reservoirs, or 0.025 mg L^{-1} within the lakes/reservoirs as per directives of the United States Environmental Protection Agency (Daniel *et al.*, 1998). A four year study on agrochemical movement in sugarcane soils in Mauritius, which was undertaken jointly by the Mauritius Sugar Industry Research Institute and the Queensland Department of Natural Resources and Mines (Australia) has shown that values higher than 0.05 mg P L^{-1} in streams flowing past sugarcane fields particularly after high rainfall events can be encountered (Ng Kee Kwong *et al.*, 2002). This observation is not at variance with the contention that P is rapidly immobilized in the soil. It simply emphasizes that only agronomically insignificant quantities of P are needed for eutrophic conditions to develop. The loss of P in surface runoff occurred mainly as sediment-bound with no evidence of P transfer in subsurface flow.

From the above it is evident that there is a need in Mauritius to protect the quality of the natural fresh water systems. As reviewed by Penn *et al.* (2006), dissolved reactive P in runoff is closely and positively correlated with soil test P in the topsoil. Thus soils with high level of extractable P are known to be at a greater risk of causing non-point dissolved P losses than low P soils. As reported by Beck *et al*. (2004) soil test P is already being used by some regulatory bodies in the United States for environmental P risk assessment and to improve actual threshold levels. To be able to maintain a soil P status that will optimise the agronomic performance of the sugarcane crop and yet will not jeopardize the quality of surface waters in Mauritius, a soil test should be proposed to the planting community to indicate not only the agronomic P status of the soils but also the potential risk of the P already present in the soil to cause an unacceptable enrichment of fresh water systems in Mauritius.

1.3 Hypotheses

A study to identify a soil P test that can be used to indicate both the agronomic and environmental P status is proposed on the basis of the above statements in section 1.2 and based on the hypotheses enumerated below.

i. Soils under sugarcane in Mauritius may contain high levels of plant-available P that are not environmentally desirable.
ii. The eutrophication of water-bodies in sugarcane growing areas is associated with the transport of P from the soils under that crop.
iii. The P fraction, which is agronomically significant in soils is prone to movement. Therefore, it may be possible to use only one chemical test to establish both the agronomic as well as the environmental threshold values.
iv. The agronomic threshold P value in soil will not be the same as the environmental threshold P value.

1.4 Objectives

The study initiated will have the following specific objectives:

iv. To review the usage of P fertilisers in sugarcane production in Mauritius and assess their resulting impact on the agronomic P status of the main soil groups under sugarcane.

v. To enlarge the scope of the current method used (0.1M H_2SO_4 extraction) for agronomic P testing so that it also indicates the environmental status of sugarcane soils in Mauritius.

vi. To determine the environmental threshold P in soils above which the P will represent a hazard to surface waters and to use that threshold P to evaluate the environmental P status of the main soil groups under sugarcane in Mauritius.

2 Literature review

2.1 Introduction

Phosphorus (P) is an essential nutrient for both plants and animals having, as reviewed by Higgs *et al.* (2000), an irreplaceable role in many physiological and biochemical processes. It is in fact the third major element required for plant growth and although P is the 11th most abundant element in the earth's crust, in most soils there is only a meagre supply of plant-available P. For this reason, input of P has long been recognised as necessary to maintain profitable crop production and, as indicated by Oberson *et al.* (1996), P deficiency is still a major constraint to agricultural productivity, affecting an area estimated at over two billion hectares of land worldwide.

The intensive use of fertilisers to remove P supply as a limitation to crop production has resulted in an accumulation of soil P, often to levels which have now become a concern to the quality of natural waters (Chen *et al.*, 2008). Phosphorus accelerates fresh water eutrophication thereby causing the water to become unfit for fisheries, recreation, industry and drinking (Sharpley and Tunney, 2000; Shigaki *et al.*, 2007). The importance of developing P management strategies so as to limit surface water eutrophication from agricultural non-point sources has therefore been recognised. In effect, the overall goal of P management practices should be aimed at balancing inputs of P from fertiliser with P output in crops and managing the soils to maintain P resources at adequate levels while at the same time minimising the transport of P from agricultural land in runoff and erosion (Daniel *et al.*, 1998).

In view of the key role which P plays in crop production and in determining the quality of freshwater resources, it has been extensively studied. A vast literature consequently exists on every aspect of P in agriculture and also in the environment. This chapter attempts to summarise the knowledge that has accumulated on firstly, the importance of P to crop growth and production, and the extent of the different sources of P available to enhance yield. A section then follows to summarise the dynamics of P in the soil and the different factors as well as reactions affecting the availability and mobility of P in the soil. Lastly

the review highlights the efficient P management practices described in the literature for crop production and for the protection of freshwater resources.

2.2 Importance of P to crop growth and production

Phosphorus, which is essential for plant growth, is involved in energy metabolisms, cellular transfer mechanisms, respiration and photosynthesis of the crop. It is taken up by the plant as the orthophosphate ions ($H_2PO_4^-$ or HPO_4^{2-}) and is incorporated into adenosine di- and tri-phosphate (ADP, ATP) required for the energy metabolism in the plant. As described by Ozanne (1980), through the combination of two photoreactions, light energy absorbed by the chlorophyll is used to reduce nicotinamide adenosine dinucleotide phosphate (NADP) to ATP. Indeed when the terminal phosphate from either ADP or ATP is split off from the molecules, a large amount of chemical energy is liberated for use in growth and reproductive systems. The high-energy phosphate compounds (ATP) in fact act as chemical intermediates which transfer energy rich $H_2PO_4^-$ molecules from ATP to energy requiring substances (ADP) in the plant (Havlin *et al.*, 2005a). This energy transfer process is known as phosphorylation.

Phosphorus is also an essential element in deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) that contain the genetic code of the plant and which play a role in producing proteins, other compounds essential for plant structure, seed yield, and in genetic transfer (Havlin *et al.*, 2005a). Phosphate also occurs in phospholipids including those of membranes, in sugar phosphates, and in various nucleotides and co-enzymes. Phytic acid, the hexaphosphate ester of myo-inositol, or its calcium or magnesium salts (phytin), serves as a storage form of phosphate in seeds (Sanchez, 2007).

One of the first symptoms of P deficiency of many plant species includes darkening of the leaves resulting in blue-green foliage. As described by Epstein (1972), often red, purple, or brown pigments develop in the leaves, especially along the veins (Figure 2.1). With increasing P deficiency, the dark green colour changes to a grayish-green to bluish-green metallic lustre. The visual P deficiency symptoms usually appear on lower leaf tips and progress along leaf margins until the entire leaf turns purple. The purple colour is due to

accumulation of sugars that enhances synthesis of anthocyanin (a purple pigment) in the leaf (Ozanne, 1980).

Figure 2.1: Purple leaf coloration observed in sugarcane as a result of P deficiency.

In the absence of adequate amounts of P, plants fail to get off to a quick start, their root systems do not develop satisfactorily, and the plants become dwarfed or become stunted as illustrated in Figure 2.2 showing narrower and shorter leaves in the sugarcane plant (Korndörfer, 2005). Phosphorus deficiency may also reduce seed numbers, their viability and size (Ozanne, 1980). Other symptoms of P deficiency in small grain crops such as wheat include poor tillering, and delayed maturity (Prasad and Power, 1997).

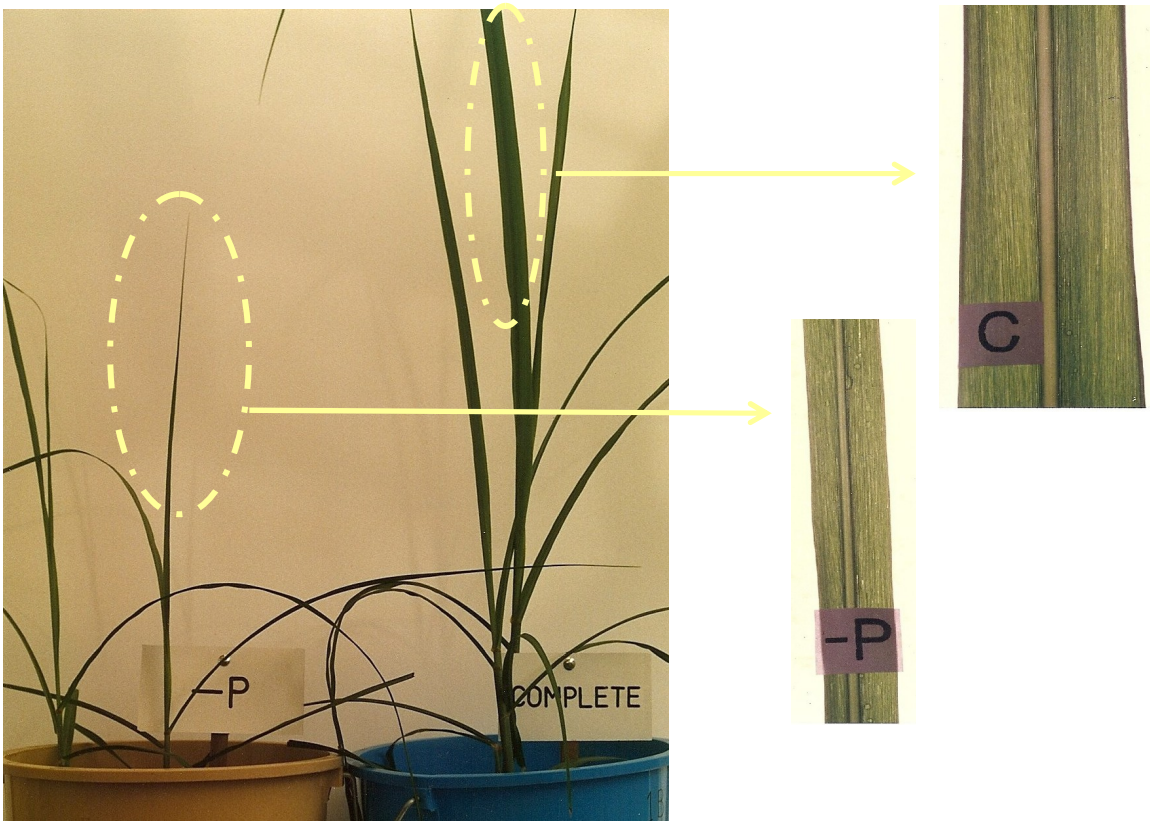


Figure 2.2: Stunted growth observed in potted sugarcane crops as a result of P deficiency.

Studies carried out by Hanway and Olson (1980) on the phosphate nutrition of maize, sorghum and soybeans showed that the total amount of P taken up for an average yield ranged from 7 to 15 kg P ha^{-1} with 2 to 8 kg P ha^{-1} being returned to the soil in the crop residues left in the field. Research on P nutrition of cereals (e.g. maize, rice and wheat) showed that for every tonne of grain produced, the total crop contained about 4.2 kg P, the range of P in the grain is given as 2.7 to 3.3 kg grain and 0.83 to 1.6 kg P in the stover (Johnston, 2005). Concerning vegetable crops such as celery, garlic, asparagus, cucumbers, and watermelons, the amount of P removed by the harvested portion of the plant is usually less than 10 kg P ha^{-1} (Lorenz and Vittum, 1980).

2.3 Phosphorus sources to crops

2.3.1 Soil P

As reviewed by Havlin *et al.* (2005a), total P in surface soils is low, varying from 0.005 to 0.15% only. This quantity has however little or no relevance to the availability of P to plants. Phosphorus in the soil occurs in organic forms as well as in inorganic compounds

which continuously undergo transformations in the soil with a consequent effect on its availability to plants. Thus, it is important to identify the different pools of soil P, to quantify their contribution to plant nutrition (Yerokun, 2008) and to understand the relationships and interactions among the various forms of P in soils as well as the numerous factors that influence the availability of P for efficient management of this nutrient.

Most naturally occurring inorganic phosphates are sparingly soluble, like those associated with calcium (Ca), aluminium (Al), iron (Fe) and manganese (Mn). Phosphate may also be held by soil clay minerals as an exchangeable anion, or may be fixed in forms unavailable for absorption by plants. The availability of P to plants is controlled by sorption, desorption, and precipitation reactions of the P released during weathering or dissolution of rocks. As stated by Peltovuori *et al.* (2001), the different forms and distribution of soil P are strongly affected by pedogenic processes which result in a vertical variability of P reserves within a soil profile.

2.3.1.1 Soil inorganic P

Mineral soils contain 50 to 70% of their total P in inorganic forms, mostly as compounds of Ca, Fe, and Al (Pierzynski *et al.*, 2000). As pointed out by Holford (1997), aluminium phosphate and iron phosphate minerals prevail in acid soils while calcium phosphates predominate in neutral and calcareous soils (Table 2.1). In acid soils, inorganic P is either precipitated as iron and aluminium phosphate secondary minerals and/or is adsorbed to surfaces of Fe/Al oxides and clay minerals. In neutral and calcareous soils, inorganic P either precipitates as the secondary minerals of calcium phosphates and magnesium phosphates in magnesium rich soils and/or is adsorbed to surfaces of clay minerals and calcium carbonate (Havlin *et al.*, 2005a).

As discussed by Brady and Weil (1996), fluorapatite is believed to be the original P mineral present in soil. It is found even in the most weathered soils, especially in their lower horizons and is an indication of the extreme insolubility and consequent unavailability of the P contained therein. The rate at which the apatites dissolve is very slow and one agricultural practical means of speeding this up is by the addition of organic matter (Brady, 1974).

Table 2.1: Common P minerals present in soils (Havlin *et al.*, 2005a).

Predominant inorganic P minerals in soils	Chemical composition
Acid soils	
Strengite	$FePO_4. 2H_2O$
Neutral and calcareous soils	
Dicalcium phosphate dehydrate (DCPD)	$CaHPO_4. 2H_2O$
Dicalcium phosphate (DCP)	$CaHPO_4$
Octacalcium phosphate (OCP)	$Ca_4H(PO_4)_3. 2.5H_2O$
b-tricalcium phosphate (b-TCP)	$Ca_3(PO_4)_2$
Hydroxyapatite (HA)	$Ca_5(PO_4)_3 OH$
Fluorapatite (FA)	$Ca_5(PO_4)_3F$

Mono- and di-calcium phosphates are readily available for plant growth. However they are present in the soil in only small quantities because they revert slowly to the more insoluble and stable forms, except on recently fertilised soils where the concentration of the available P from these sources may be relatively high for a given period of time (Prasad and Power, 1997). Much less information is available on the Fe-P and Al-P contained in soils except that they are highly stable and extremely insoluble (Brady and Weil, 1996).

2.3.1.2 Soil organic P

Organic P represents 50% of the total P in soils and may vary between 15 and 80% (Havlin *et al.*, 2005a). This high variability may be explained by the fact that the organic P in soil depends upon a number of factors including climate, vegetation, soil, texture, land use pattern, fertiliser practices, drainage, and irrigation (Prasad and Power, 1997). Three groups of soil organic P compounds have been identified so far and they are all present in plants. They are inositol phosphates (phosphate esters of inositol, $C_6H_6(OH)_6$), nucleic acids, and phospholipids (Table 2.2).

Table 2.2: Forms of organic P in soils (Prasad and Power, 1997).

Form	Soil (mg kg^{-1})	% of organic P
Inositol phosphate	1.4 -356	0.3-62
Nucleic acid	0.1-97	0.1-65
Phospholipids	0.4-17	0.03- 5.4

Inositol phosphates are thought to be of microbial origin and represent a series of phosphate esters ranging from monophosphate to hexaphosphate. They exist in several stereoisomeric forms; phosphate esters of myo-, scyllo-, neo-, and chrio-inositol have been characterised in soils (Cosgrove, 1962). Myo-inositol hexaphosphoric acid (phytic acid) is usually the major pool of organic P and occurs widely in nature. It is fairly stable in an alkaline medium, but gradually hydrolyses to a range of intermediate inositol phosphates and finally to inositol in acidic media, the optimum pH for hydrolysis being near 4.0. Enzymes phytases also hydrolyze myo-inositol phosphates.

Nucleic acids occur in all living things and exist in two distinct chemical forms namely, ribonucleic acid (RNA) and deoxyribonucleic acid (DNA). After surveying the existing literature, Harrison (1987) reported values ranging from 0.1 to 9 mg P kg^{-1} as nucleic acids which actually represent 0.1 to 65% of organic P. Phospholipids, on the other hand are derivatives of glycerol and are insoluble in water. They have been defined by Pierzynski (1991) as organic phosphates that are soluble in fat solvents such as ether and benzene. Like nucleic acids, they are readily degraded by soil microbes and eventually represent only a small portion of total organic P.

Organic P contributes to P nutrition of plants, primarily after being mineralised into inorganic P (Oberson *et al.*, 1996). The rate of P mineralisation depends on both microbial activity in the soil and on the activity of the free phosphatases (Dalal, 1977). Moreover, the availability of organic P for plant uptake also depends on the behaviour of the organic compounds in the soil. It follows that in acid soils phytins form iron and aluminium phytases while under alkaline conditions they precipitate as calcium phytates. In both cases they are rendered insoluble and unavailable to plants (Brady, 1974). Nucleic acids are adsorbed to clay minerals, especially montmorillonite, resulting in a marked decrease in their rate of decomposition and also in their P availability to plants. While phytins may be absorbed directly by the plants, nucleic acids must be broken down by enzymes at the root surfaces and the P released may be absorbed in either the organic or inorganic form (Brady, 1974).

As a result of the relative unavailability of the two sources of P in soil (i.e. inorganic and organic soil P) to the plant together with the fact that their fractions which are in an accessible state are insufficient to meet the nutrient P requirements of crops, an external P supply in the form of mineral P fertilisers or organic waste materials must therefore be added to optimise crop production.

2.3.2 Mineral P fertilisers

Phosphate mineral deposits, which are non-renewable natural resources, are widespread throughout the world, occurring in all continents with the exception of Antartica. The global reserves of apatite which is used for producing P fertilisers are nevertheless limited and with the current expansion in P usage, known reserves may be exhausted in about 100 years (Lehmann *et al.*, 2001). The average abundance of P in the earth's crust is itself 1.0 g kg^{-1} which is equivalent to 0.22% P_2O_5 (Stewart *et al.*, 2005).

Depending upon their origin and the weathering conditions that have prevailed, phosphate rocks have widely differing mineralogical, chemical and textural characteristics (Stewart *et al.*, 2005) and so far almost 170 different minerals have been identified (Holford, 1997). These different minerals vary in solubility, and tend to change with time from sparingly soluble compounds to more insoluble ones. According to McClellan and Gremillion (1980), phosphate deposits on the basis of their mineral assemblages may be classified into three broad groups; namely Fe-Al phosphates, Ca-Fe-Al phosphates and Ca phosphates.

As indicated by Stewart *et al.* (2005), the commercial mining of phosphate deposits began in the mid-19th century and increased on a worldwide basis from 5 000 t in the 1850s to more than 100 Mt in the 1970s. In 2000, the world production of rock phosphate was about 133 Mt with the United States currently the largest producer, accounting for 28% of the output, followed by China (21%), Morocco and Western Sahara (15%), Russia (8%) and Tunisia (6%). About 80% of the rock phosphate produced worldwide is utilised for

fertiliser production while the remaining 20% is used in the manufacture of detergents (12%), animal feed (5%) and in specialty applications (Stewart *et al.*, 2005).

A considerable variety of commercial forms of fertiliser P is currently produced and sold on the world market (Table 2.3). As highlighted by Havlin *et al.* (2005a), finely ground sedimentary rock phosphate can supply adequate plant available P in low pH soils (i.e. acid soils) when applied at relatively high doses (two to three times the rates of superphosphates). The use of rock phosphate in strongly weathered and P deficient acidic soils of the humid forest agroecosystems of West Africa has shown to be agronomically responsive and economically profitable because the price of a unit P in the rock phosphate can be as little as one third the price of a unit P in commercially available superphosphates (Oikeh *et al.*, 2008). In situations where rock phosphate reactivity is insufficient for immediate crop uptake, or where the P-fixation capacity of the soil quickly renders soluble P fertiliser unavailable to plants, the rock phosphate is acidulated using either phosphoric or sulphuric acid in order to increase the water-soluble P content and to improve the short-term crop response to the rock phosphate (Havlin *et al.*, 2005a). Troeh and Thompson (1993) emphasized the simultaneous use of manure and rock phosphate in order to supplement one another. Upon decomposition, the manure produces organic acids which help dissolve the insoluble rock phosphate.

The most commonly used P fertilisers at present are the ammonium phosphates, which are available commercially as both di- and mono-ammonium phosphates (DAP and MAP respectively). Although ammonium phosphates were known to be an effective source of nutrients to plants since the early 1900s, it was not until the 1960s that they began to dominate the market place (Leikan and Achorn, 2005). In addition to providing P, ammonium phosphates are also excellent nitrogen sources (Table 2.3). The increased interest in the use of ammonium phosphate fertilisers has stemmed from the fact that the presence of ammonium ions (NH_4^+) has a stimulating effect on P absorption by roots (Havlin *et al.*, 2005a).

Table 2.3: Major sources of P for crop production (Pierzynski *et al.*, 2000).

P source and chemical composition		P (%)	P_2O_5 (%)	Other nutrients
Rock phosphates	$Ca_{10}F_2(PO_4)_6.XCaCO_3$ (varies between mineral deposits)	14 -17	33-39	Major impurities: Al, Fe, Si, F, CO_3^{2-}
Commercial fertilisers				
Single superphosphate	$Ca(H_2PO_4)_2 + CaSO_4$	7-10	16-23	Ca, S (8-10%)
Triple superphosphate	$Ca(H_2PO_4)_2$	19-23	44-52	Ca
Monoammonium phosphate (MAP)	$NH_4H_2PO_4$	26	61	N (12%)
Diammonium phosphate (DAP)	$(NH_4)_2HP0_4$	23	53	N (21%)
Ammonium polyphosphates (liquids)	$(NH_4)_3HP_20_7$	15	34	N (11%)
Organic P sources				
Cattle manure		0.9	2.1	N, P, K, S, Ca, Mg, and trace elements
Dairy manure		0.6	1.4	
Poultry manure		1.8	4.1	
Swine manure		1.5	3.5	
Composted sludge		1.3	3.0	

Calcium phosphate fertilisers are also an important source of P, and they exist commercially as single superphosphate (SSP) and triple superphosphate (TSP). Single superphosphate also known as normal or ordinary superphosphate was the principal phosphate fertiliser for more than a century, supplying over 60% of the world's phosphate in 1955 (Anon, 1998). Its relative importance as a P fertiliser has since declined and in 1988, it supplied only 17% of the world phosphate fertiliser. While the SSP contains 16 to 22% P_2O_5, TSP has an available P_2O_5 content of 44% to 52% and it is the most highly concentrated straight phosphate fertiliser available (Table 2.3). Other less popular forms of commercial P fertilisers mentioned in the literature (e.g. Leikan and Achorn, 2005) include liquid ammonium polyphosphates and nitrophosphates.

Data from the International Fertiliser Association as quoted by Higgs *et al*. (2000) show that the world P fertiliser consumption (expressed in terms of P_2O_5) increased almost linearly from just over 4.4 Tg in 1960 to a peak of around 16.4 Tg in 1988-1989. In 1984, P fertiliser use in developed countries was 9.7 Tg, almost twice that of the developing nations (5.3Tg). By 1995 this situation had changed dramatically with use in the developing countries increasing to 8.3 Tg, and being around 50% more than that of the developed countries (5.4 Tg). This increase in P use in the developing countries was due to recognition of the need to raise the P status of the soils on those countries in order to increase crop production. The decrease in P use in the developed countries can on the other hand be explained by the necessity to protect the environment in particular the freshwater resources, from the excessive P fertilisation of the past.

2.3.3 Organic P sources

The most common organic P sources to plants are animal manures and sewage sludge. In comparison to mineral P fertilisers, all the wastes are dilute sources of fertiliser P containing in general less than 2% P (Table 2.3). This implies that large volumes of wastes must be used to satisfy the P requirements of the crops. Due to the greater N than P requirement of crops and the approximately equal N and P levels in most organic sources, application rates of the latter based on N provide P in excess of that required for crop growth (Sommers and Sutton, 1980). Also another difference when compared to mineral P fertilisers is that a considerable fraction of the P in the organic sources is in organic form and hence can only contribute to the P nutrition of plants after being mineralized to the orthophosphate ($H_2PO_4^-$ or HPO_4^{2-}) ions (Oberson *et al*., 1996).

Sludges are generated in nearly all sewage treatment plants and the composition of sewage sludge is dependent upon the type of treatment process. As reviewed by Korentajer (1991), sewage sludge can be used as a P source in highly weathered soils particularly in perennial crops such as sugarcane. The NPK content of sewage sludge is quite variable at a particular treatment plant, varying with time as a result of microbial activities and mineralisation (Sommers and Sutton, 1980). In general however the P

content of sewage sludge ranges from 2 to 4% (Table 2.3). Between 70 and 90% of the total P in the sludge is present as inorganic P while the remaining portion exists in organic P form and originates from microbial cells and their degradation products (Sommers *et al.*, 1976). The presence of a relatively high concentration of metal cations (Ca, Fe, Al, and Mn) in the sludge results in the sorption of the inorganic P fraction onto the amorphous hydrous oxides or in its precipitation as metal phosphates (Sommers and Sutton, 1980).

Even though, most of the P present in sewage sludge appears to be available for plant uptake, the P is most often not the growth-limiting nutrient which means that other nutrients, especially N must be added in order to obtain maximum crop yields. However, the capacity of the sewage sludge to meet crop N requirements is hindered by the fact that ammonia volatilisation occurs especially when the sewage sludge is surface applied (Sommers and Sutton, 1980). An additional complicating factor in evaluating the effect of sewage sludge as a P source is the presence of metals which may be essential to the crop at low concentrations but toxic to it at higher levels.

As indicated in Table 2.3, the chemical composition of livestock manures varies greatly, depending on the species and physiology of the animal, the ration fed to the animal, the waste management system and the climate (Sommers and Sutton, 1980). The organic P content of animal wastes is approximately 30% of the total P. Most of the organic P is of unknown chemical structure, though phospholipids and inositol hexaphosphate-P have been identified to be present in all manures (Sommers and Sutton, 1980). As reviewed by Motavalli and Miles (2002), the long-term application of animal manures and other organic amendments increased total P, available P and soluble P levels in both the surface and subsurface horizons but reduced P adsorption capacity of the soil. Thus repeated applications coupled with the fact that, just as with sewage sludge, manure rates are based on N requirements of the crop with little consideration given to crop P needs, eventually result in an excessive soil P status (Pote *et al.*, 1996) which thereafter becomes a hazard to the environment.

2.4 Phosphorus dynamics in soils

2.4.1 Soil P availability to crops

The dynamics of P in soils can best be described by showing the soil P cycle such as the one proposed by Pierzynski *et al.* (2005) and reproduced in Figure 2.3.

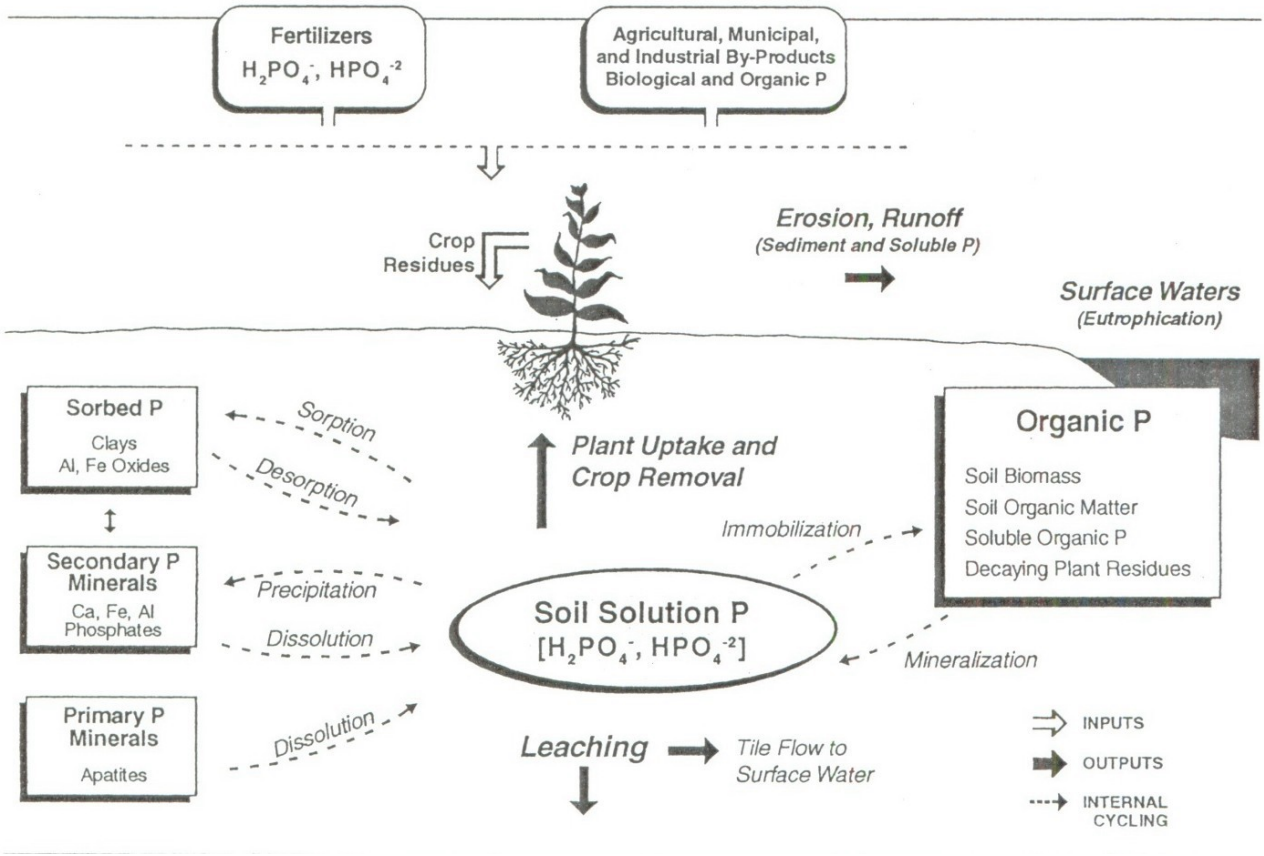


Figure 2.3: The soil P cycle as described by Pierzynski *et al.* (2005).

From the viewpoint of plant nutrition and availability to crops, the P in soil has most conveniently been categorised into three forms, namely *solution P*, *labile P* and *non-labile P* (Pierzynski *et al.*, 2005). The relationship among these three forms of P is often simplified to the following equilibrium equation (Beaton and Nelson, 2005).

Soil solution P ⇌ Labile P ⇌ Non-labile P

Phosphorus occurs in the soil solution as orthophosphate ions, $H_2PO_4^-$ and HPO_4^{2-}, which are in fact the only forms of P that can be taken up by crops. They therefore constitute the

primary source of P for plants (Condron *et al.*, 2005). As reviewed by Pierzynski *et al.* (2005), soil solution P generally represents less than 1% of the total quantity of P in the soil.

In order to maintain the concentration of P in soil solution at an optimum value for plant growth (>0.2mg L^{-1}), the chemical and biochemical processes of the soil P cycle all come into play to release P rapidly through dissolution-precipitation, sorption-desorption, mineralisation-immobilisation, and oxidation-reduction reactions (Pierzynski *et al.*, 2005).

The soil or sediment P that equilibrates *rapidly* with the solution P is referred to as the labile P. It is therefore the readily available P in the soil that exhibits a high dissociation rate to rapidly replenish soil solution P (Pierzynski *et al.*, 2005). On the other hand, the forms of P that are *slow* to equilibrate with the labile P and solution P are termed non-labile and constitute the bulk of the soil P (Pierzynski *et al.*, 2005). As labile P from the soil is depleted (e.g. due to plant uptake), some non-labile P becomes labile but this usually occurs at such a slow rate that most of that fraction can be considered to be unavailable to crops.

While the inorganic P forms in soils equilibrate with the soil solution P through adsorption-desorption reactions and through dissolution-precipitation, the organic P component influences the P concentration in the soil solution through mineralisation and immobilisation (Pierzynski *et al.*, 2000). Both P mineralisation and immobilisation rates are affected by factors such as temperature, moisture, aeration, pH, cultivation intensity and P fertilisation (Havlin *et al.*, 2005a). The extent of P mineralisation over immobilisation depends on the C:P ratio of the residues deposited in the soil (Stevenson, 1964). Mineralisation occurs rapidly if the C:P ratio of the organic matter is less than 200:1, while immobilisation will be predominant if the C:P ratio exceeds 300:1 (Pierzynski *et al.*, 2000).

2.4.2 Phosphorus fertiliser transformations in soil

When soluble phosphatic fertilisers are applied to soils, they initially dissolve causing an immediate rise in the concentration of soil solution P, which then participates primarily in

adsorption and precipitation processes (Prasad and Power, 1997). The reactions that occur among the phosphate ions present in the soil solution, the soil constituents, and the non-phosphatic components in the fertilisers, primarily remove the P from the solution phase and render the phosphate less soluble over time (Sample *et al.*, 1980). This phenomenon is commonly referred to as *P fix*ation or retention. As a consequence of the fixation P becomes highly immobile in soils and generally stays near the point of application (Prasad and Power, 1997). In fact, at the beginning the sorption processes are easily reversible and the added P remains readily available for plant uptake, thereby imparting a high residual value to the phosphate fertiliser (Havlin *et al.*, 2005a).

The solid labile phases formed initially however gradually revert to less soluble P forms (non-labile) and adsorption continues to decrease soil solution P concentration with time and to cause a reduction in plant available P (Pierzynski *et al.*, 2005). Fixation of P by soils thus plays an important role in determining the ultimate availability of fertiliser P to crops and its mobility in soils. On account of its significant role in affecting the availability and mobility of P, an understanding of the different reactions underlying P fixation in soils is a first step towards obtaining optimum P nutrition and towards achieving efficient management of the fertiliser P to protect freshwater sources.

2.4.2.1 Fixation of P by hydrous oxides of Fe and Al

The most active soil constituents involved in the retention of P in the soils are the hydrous oxides of iron and aluminium. These oxides occur either as discrete compounds in soils or as coatings on soil particles or as amorphous Al hydroxyl compounds between the layers of expanding Al silicates. Studies carried out (e.g. Sample *et al.*, 1980) have shown that these hydrous oxides of Fe and Al retained large amounts of P from soil solution, the amount of P sorbed by hydrous oxides of iron and aluminium being dependent upon the time of reaction, the temperature, pH and the P concentration in the soil solution. Bache (1964) studied P sorption by gibbsite and hydrous ferric oxide and showed that the mechanism of P retention in soils by the Al and Fe oxides followed three distinct stages which occur at different P concentrations in the solution: (i) a high energy chemisorption,

(ii) precipitation of a separate phosphate phase, and (iii) a low energy sorption of P onto the precipitate.

In acid soils, the predominance of positive charges on Al and Fe oxides/ hydroxides facilitates the attraction of negatively charged orthophosphate $H_2PO_4^-$ and HPO_4^{2-} ions (Havlin *et al.*, 2005a). The mechanism of P adsorption on Al/Fe oxide surface involves the exchange of phosphate for OH groups as shown in Figure 2.4.

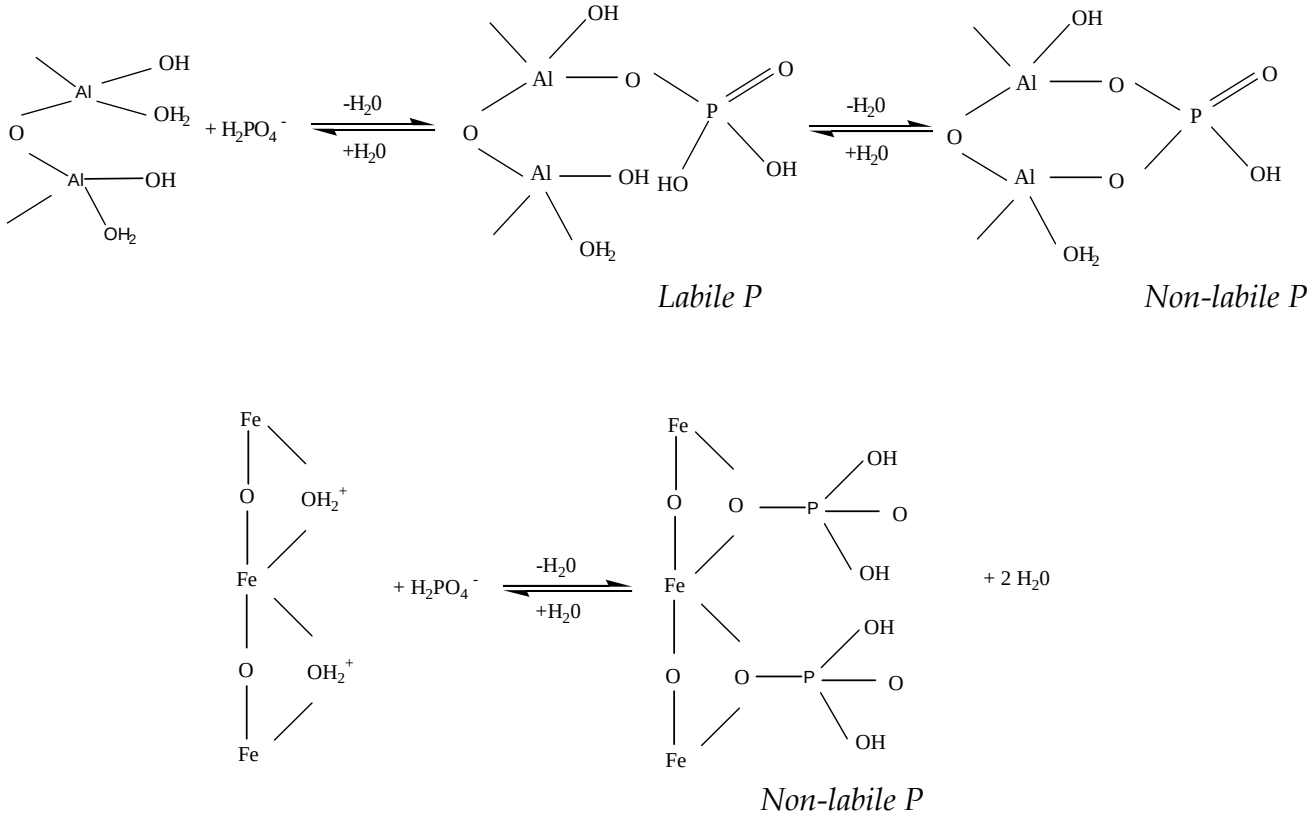


Figure 2.4: Mechanism of P adsorption to Fe/Al oxide surface (Havlin *et al.*, 2005a).

When the orthophosphate ion is bonded through one Al-O-P bond, the $H_2PO_4^-$ is considered as labile as it can readily be desorbed from the mineral surface to soil solution. But when the $H_2PO_4^-$ is bonded to the Fe/Al hydroxides through two Al-O bonds, a stable six-membered ring is formed and the $H_2PO_4^-$ is regarded as non-labile and unavailable for plant uptake.

As reviewed by Sample *et al.* (1980), at low solution P concentrations hydrous oxides retain P through sorption-type reactions but at higher P concentrations, that is when the concentration of P and associated cations in the soil solution exceeds that of the solubility product (K_{sp}) of the mineral, precipitation reactions are favoured. In neutral and calcareous soils, Ca being the dominant cation, the addition of soluble P initially results in the precipitation of di-calcium phosphate dihydrate {$CaHPO_4.2H_2O$} which, with time slowly reverts to other more stable but less soluble Ca phosphates (Pierzynski *et al*., 2000). The precipitates in Ca systems as described by Sharpley (2000), usually occur in the following sequence: mono-calcium phosphate {$Ca(H_2PO)_4)_2$}, di-calcium phosphate dihydrate {$CaHPO_4.2H_2O$}, octa-calcium phosphate {$Ca_8H_2(PO_4)_6.5H_2O$} and finally hydroxy-apatite {$Ca_{10}(PO_4)_6(OH)_2$} or fluoro-apatite {$Ca_{10}(PO_4)_6F_2$}.

The chemical equation given below summarises the precipitation reactions involving soluble Fe or Al with $H_2P0_4^-$ in acid soils to form Al or Fe hydroxyl-phosphates (Brady, 1974).

$$Al^{3+} + H_2P0_4^- + 2H_2O \rightleftharpoons 2H^+ + Al(OH)_2H_2PO_4$$

As reviewed by Sharpley (2000), generally P in the soil solution reacts with Al oxides to form amorphous Al-P organized phases such as sterretite { $Al(OH_2)_3.HPO_4.H_2PO_4$}; and with Fe oxides to such precipitates as tinticite {$Fe_6(PO_4)_4(OH)_6.7H_2O$} or griphite {$Fe_3Mn_2(PO_4)_2.5H_20$}.

2.4.2.2 Fixation of P by soil alumino-silicate minerals and carbonates

Alumino-silicate minerals, such as kaolinite, montmorillonite and illite also play a significant role in P fixation (Brady and Weil, 1996). Phosphorus is adsorbed to a larger extent by 1:1 clays (e.g. kaolinite) than by 2:1 clays (e.g. montmorillonite). This can be explained by the presence of higher amounts of Fe/Al oxides associated with kaolinitic clays. Moreover in the kaolinitic clays, a larger number of OH groups are exposed in the Al layer to exchange with P (Havlin *et al.*, 2005a). In addition, the presence of pH-dependent charges on kaolinitic clays also contributes to P adsorption. The mechanisms of P adsorption by alumino-silicate minerals are therefore the same as described above for the oxides of Al and Fe. Thus at low P concentrations, the P is adsorbed onto the silicate

clays with the replacement of surface hydroxyl groups as illustrated in Figure 2.4. At high P concentrations such as soon after application of soluble mineral P fertilisers, the P solutions dissolve the alumino-silicate minerals to release Si and Al with the subsequent precipitation of Al-P compounds (Sample *et al.*, 1980).

In calcareous soils, P adsorption may also occur on soil carbonates ($CaCO_3$). As reviewed by Prasad and Power (1997), the interaction of P with $CaCO_3$ involves two reactions: the first reaction occurs at low P concentration and consists of adsorption of P on $CaCO_3$ surfaces, while the second reaction is a nucleation process to form phosphate crystals.

The different above-mentioned reactions of added P in soils described in this section and in the preceding one explain the high residual values of P fertilisers that are often reported in the literature (Havlin *et al.*, 2005a). As indicated by Morel and Fardeau (1989), 80-99% of P applied as fertilisers remains in the soil. In fact as summarised by Barrow (1980), the literature available on the residual value of P fertilisers has two contrasting strands. First, a reported decline in effectiveness of the P fertilisers over the first few months (or years) after their application implying that repeated applications of P is required and second, mention is frequently made about the continuing uptake of P by crops for several years after application and on the long term recovery of added P. The residual availability potential for such immobile nutrients as P can only be accurately assessed through soil testing (Havlin *et al.,* 2005b) and is discussed in section 2.5.2.

2.4.3 Factors and reactions affecting P availability and mobility

It follows from the preceding sections that in general, P retention or fixation in soils is a continuous process involving precipitation, chemisorption and adsorption (Prasad and Power, 1997). As mentioned, P retention follows an adsorption mechanism at low solution P concentrations while at high P concentrations in solution precipitation predominantly occurs following solubility product principles. As the availability and mobility of P in soils are highly influenced by P retention, the soil properties influencing P retention and solubility need to be known and are discussed in this section.

2.4.3.1 Soil P buffering capacity

The soil P buffering capacity is an important soil property providing a suitable indication of available P in the soil (Holford, 1997). McDowell *et al.* (2001) added that since soil P buffering capacity is a function of sorption capacity and sorption strength, it controls the rate of desorption and diffusion of P from soil to solution. The higher the soil P buffering capacity, the slower but the longer P will be replenished in the soil solution following its absorption by plant roots. As explained by Holford (1997), this replenishment capacity depends on the quantity of P in the labile pool and the ease with which this P is released into solution.

2.4.3.2 Soil mineralogy and clay content

Adsorption and desorption reactions are affected by the type of mineral surfaces in contact with P in the soil solution (Havlin *et al.*, 2005a). As explained in section 2.4.2.1 and 2.4.2.2, P is adsorbed most extensively by Al and Fe oxides and to a greater extent by 1:1 clays (such as kaolinite) as compared to 2:1 clays (e.g. montmorillonite) due to the presence of higher Fe/Al oxides content in the 1:1 clay minerals (Havlin *et al.*, 2005a). Apart from the nature of the minerals, the clay content of soils also affects the degree of P fixation. Among soils of similar clay mineralogy, P fixation obviously increases with increasing clay content (Kamprath and Watson, 1980). Thus soils with a sandy texture have low P adsorption capacities with the P more susceptible to leaching (Pierzynski *et al.*, 2000).

In calcareous soils, the presence of $CaCO_3$ with large surface area also shows a high adsorption and a rapid precipitation of Ca-P minerals (Havlin *et al.*, 2005a). Calcareous soils with highly reactive $CaCO_3$ and a high Ca-saturated clay content have in this context been shown to exhibit low solution P levels, since the P in the soil solution is instantaneously precipitated or adsorbed (Havlin *et al.*, 2005a).

The type of cations on the cation exchange sites of the clays also has an effect on P adsorption (Havlin *et al.*, 2005a). Ca-saturated clays have been shown in this context to exhibit greater P adsorption than Na-saturated clays. As reviewed by Kurtz (1953), even at

pH levels below neutrality, where calcium precipitation would not be expected, calcium clays retain more phosphate than sodium, ammonium or potassium clays. This observation was explained by a possible precipitation of calcium phosphate at the colloid surface or a binding of phosphate to the soil colloid through Ca^{2+} on the exchange complex (Kurtz, 1953).

2.4.3.3 Soil pH

Phosphorus fixation in acidic soils is more pronounced than in calcareous/alkaline soils. The P adsorbed is also held more strongly. In fact, in most soils, maximum P retention occurs at low pH values of 3.0 to 4.0 because of adsorption by Fe/Al oxides. As the pH increases, P adsorption decreases resulting in a higher concentration of P in soil solution (Havlin *et al.*, 2005a). In general, P availability to plants in most soils will be at its maximum when the soil pH is maintained in the range from 6.0 to 7.0 (Brady and Weil, 1996). Above pH values of 7, the presence of $CaCO_3$ accounts for P fixation, resulting in a decline of soil solution P.

2.4.3.4 Soil organic matter

Soil organic matter in association with cations such as Fe, Al and Ca is capable of retaining significant amounts of P (Prasad and Power, 1997). Humic acid dissolves Al from soil minerals to form complexes which eventually give rise to new surfaces for P adsorption by ligand exchange of the phosphate ions for the hydroxyl groups (Sample *et al.*, 1980). Hence the overall effect of an increase in organic matter content of the soil would be an increase in P adsorption. On the other hand, as also described by Sample *et al.* (1980) in calcareous soils, organic matter and P compete for the same adsorption sites on $CaCO_3$, thereby decreasing the ability of the calcareous soils to adsorb P.

The presence of organic compounds in soils has also been reported to increase P availability by maintaining the P in solution through the formation of stable complexes with Fe and Al (Prasad and Power, 1997). The organic anions known to be most effective in competing and replacing $H_2PO_4^-$ are citrate, oxalate, tartrate and malate (Havlin *et al.*, 2005a). In soils with very high organic matter, P mobility is further enhanced by the organic matter forming a coating on the colloidal surfaces responsible for P adsorption

(Pierzynski *et al.*, 2000). This explains why organic compounds tend to move P to a greater depth than would inorganic P in soil solution. In this context, the continuous application of manure has been found to result in elevated P levels at 0.6 to 1.2 m soil depths while the application of the same amount of P as inorganic fertilisers resulted in much less downward movement of P (Havlin *et al.*, 2005a).

2.4.4 Environmental pollution by P

As reviewed by Hodgkinson and Withers (2007) and explained in section 1.2, P loss from agricultural land has become an increasing environmental concern because of its significant impact on the eutrophication of natural freshwater resources. Phosphorus, as was further stated, is most often the nutrient limiting accelerated eutrophication because many algae are able to utilize atmospheric nitrogen (Pote *et al.*, 1996). Agricultural non-point source pollution as a result of P fertilisation may be attributed to the evolution of agricultural systems from net sinks of P (i.e. deficits of P limit crop production) to net sources of P (i.e. P inputs in manures and mineral fertilisers exceed outputs in agricultural produce).

As also mentioned in section 1.2, to control eutrophication total P should not exceed 0.05 mg L^{-1} in streams entering lakes/reservoirs, or 0.025 mg L^{-1} within the lakes/reservoirs. For the prevention of plant nuisances in streams or other flowing waters not discharging directly to lakes/impoundments, the concentration of total P should not exceed 0.10 mg L^{-1} (Smith, 1996). On the other hand, regulators in The Netherlands have set a critical limit of 0.10 mg L^{-1} as dissolved P tolerated in ground water (Sharpley, 2001). Though there is no clear, widely accepted agreement as to what concentrations of total P should be tolerated in fresh water systems to avoid eutrophication, the point is that these values of acceptable P in freshwaters are an order of magnitude lower than the P concentrations in soil solution required or critical for plant growth (0.2 - 0.3 mg L^{-1}). For most lakes, streams, estuaries and reservoirs, concentrations of 100 µg total P L^{-1} are unacceptably high and concentrations of 20 µg L^{-1} can even be a problem (Correll, 1998).

Research carried out since the early 1970s (e.g. Lemunyon and Gilbert, 1993; McDowell *et al.*, 2001; Shigaki *et al.*, 2007) on the transfer of P from soil to waterways have shown that P is transported to water bodies by overland flow (erosion and runoff) or by subsurface flow (leaching). Usually, the amount of soluble P present in runoff waters is low due to the low solubility of P in soils and the considerable P adsorption capacities of clays. The major fraction of P in runoff occurs as particulate P especially when the runoff contains high quantities of suspended solids (Pierzynski *et al.*, 2000). While dissolved reactive P in runoff is immediately available for uptake by aquatic biota and promotes fresh water eutrophication, a variable portion of particulate P represents a secondary and long term source of bioavailable P in lakes (Sharpley, 1993). The concentrations of P in subsurface flow have been found to be quite low and are well below eutrophication threshold (Pierzynski *et al.*, 2000).

2.5 Phosphorus management for crop production

2.5.1 Management of P fertilisers for optimum crop production

The efficiency with which P fertilisers are used by crops depends not only on the extent of P deficiency in soils and on crop P requirements but also on factors such as the time of application, placement, rate and frequency of the fertiliser P applications (Havlin *et al.*, 2005c). All of these factors, by influencing P fixation reactions in the soil, eventually determine P availability and uptake by crops.

The timing of P fertilisation from an agronomic perspective is optimised if adequate amounts of P are available at all times to meet plant requirements (Bundy *et al.*, 2005). Phosphorus is needed as from the earliest stages of crop growth since it is important in nearly all energy-requiring processes in the plant. As indicated by Bundy *et al.* (2005) the use of starter P fertilisers is known to increase early plant growth and development. As P stress early in the growing season reduces crop productivity more than P restrictions later during the crop season, P fertilisation is usually best carried out just before or at planting.
The placement of the starter P fertiliser also plays an important role in its effectiveness to crops (Bundy *et al.*, 2005). Phosphorus is relatively immobile in the soil and so remains near the site of fertiliser placement (Grant *et al.*, 2001). Surface application after the crop

has been planted will not place the P near the root zone and will thus be of little value to annual crops in the year of application (Havlin *et al.*, 2005c). For optimum P management, the question of band placement over broadcast application is an important consideration. As pointed out by Havlin *et al.* (2005c), band placement of P reduces fertiliser-soil contact, resulting in less fixation than broadcast P. This implies that P is maintained in a plant-available form for a longer period of time.

In fact to ensure maximum P efficiency, a compromise between reducing the volume of soil fertilised so as to minimise fixation and providing a large enough fertilised soil volume to encourage root-fertiliser contact has to be found (Grant *et al.*, 2001). Phosphorus being immobile and not moving easily through the soil, must be placed in a position where the plant roots can contact it early in the season. Therefore, soluble fertiliser P is most efficient when seed-placed or placed in a band close to the seed (Grant *et al.*, 2001) especially for crops having poorly developed root systems. However, seedling damage is often observed when P is placed in the seed-row. Such damages are more prominent when mono-ammonium or di-ammonium phosphates are utilised and to avoid this problem of seed damage, banding the fertiliser below the seed-row is the best practice (Grant *et al.*, 2001).

The question on frequency of fertiliser P application in crop rotations or in permanent pastures is pertinent throughout the range of P-deficiency levels encountered in soils. Frequent P applications are likely to be more important with soils of high P fixation capacities than with soils of low P fixing properties (Stanford and Pierre, 1953). In general the repeated application of large amounts of P fertiliser to crops eventually result in a point where a single application at the time of planting will suffice to give optimum crop yields. Recent studies on the response to P fertilisation by ratoon cane have even shown that on some sugarcane farms the application of P to ratoon cane can be reduced for several years without a decline in productivity (Korndörfer, 2005).

As mentioned in section 2.3.2, the utilisation of rock phosphate to supply plant-available P in strongly weathered and P deficient acidic soils has been found to be agronomically

responsive. The efficacy of the rock phosphate depends on its dissolution which is influenced by many factors, including soil pH (Yusdar *et al.*, 2007) and the fineness of grinding of the phosphate rock. From an agronomic point of view, while water-soluble fertilisers should be applied in bands as explained above, rock phosphates on the contrary will be most effective when broadcasted throughout the field (Gilkes and Bolland, 1990). This is so because the dissolution of the rock phosphate will be enhanced when its degree of contact with the soil H^+ ions is enhanced (Gilkes and Bolland, 1990).

2.5.2 Assessment of P needs of crops

2.5.2.1 Plant testing

The quantity of P required by crops depends on many interacting factors such as the environment (water, temperature and sunlight) and the soil management practices (Havlin *et al.*, 2005b). The quantity of P required to optimise crop yield further depends on both the plant P requirements and on the P-supplying capacity of the soil. Diagnostic techniques commonly employed to assess the P status of a soil include the identification of plant P-deficiency symptoms, plant testing and soil analysis (Sumner, 2006).

Plant testing in a narrow sense is described as the determination of the concentration of an element such as P or of an extractable fraction of the element in a particular part of a crop when sampled at a certain time or stage of morphological development (Walsh and Beaton, 1973). Plant testing involves either field tests which are performed on fresh tissue or laboratory-based analysis of the plant tissue. It is based on the premise that the amount of a given nutrient in a plant is related to the availability of that nutrient in the soil (Havlin *et al.*, 2005b). In essence plant testing helps to identify deficiency symptoms or to determine nutrient shortages before they appear. In this context, though visual deficiency symptoms provide an indication of P deficiency, they are seldom conclusive. Consequently accurate diagnosis typically requires a tissue test (Sanchez, 2007). In conjunction with soil tests plant testing may also aid in determining the P-supplying capacity of the soil.

Diagnostic standards with respect to plant testing involve the utilisation of critical levels or sufficiency ranges (Sanchez, 2007). These levels or ranges are usually determined by developing a response curve relationship as shown in Figure 2.5. As reviewed by Westermann (2005), the critical nutrient range is the range of concentrations above which the crop is amply supplied and below which the crop is deficient in the nutrient investigated. Usually the diagnosis of a nutrient deficiency, including P deficiency, by tissue analysis is a post-mortem of the current fertilisation practices (Sanchez, 2007) and is used to correct impending shortages of the nutrient in future crops.

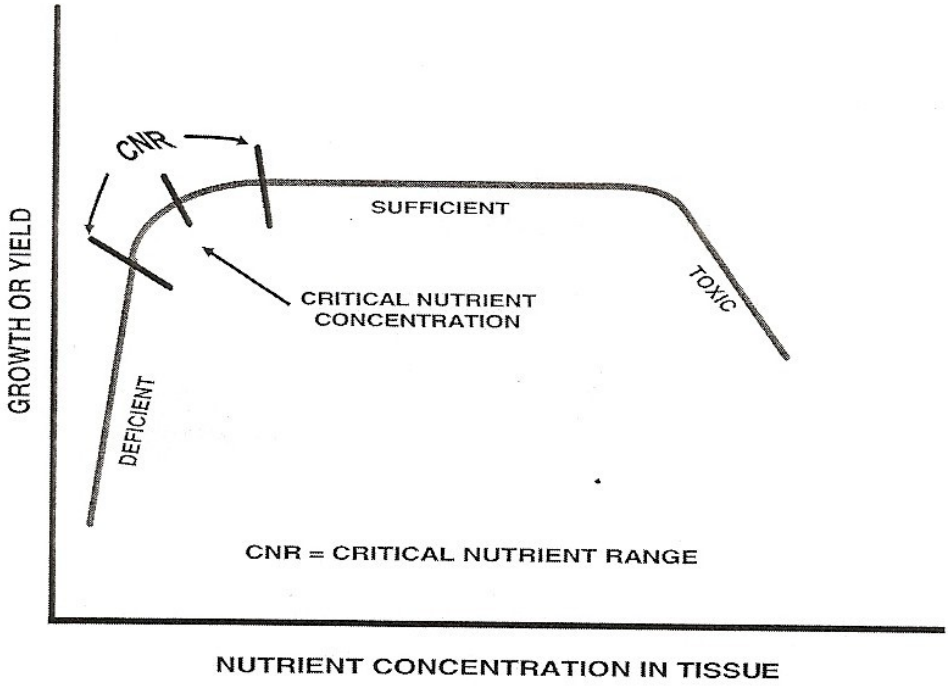


Figure 2.5: Growth or yield of plants in relation to nutrient concentration in plant tissue (Westermann, 2005).

2.5.2.2 Soil testing

Soil testing is an essential and integrated part of soil management in present-day agricultural systems (Fageria *et al.*, 1997). Crop response is poorly related to the total amount of P in a soil and therefore a successful soil test should represent some index of P availability (Sanchez, 2007). Agronomic soil tests to indicate available P have been designed such that (i) they are simple for routine application, (ii) they extract sufficient P to be easily measurable, (iii) they extract sufficient P to represent a significant portion of

the soil P potentially available for plant uptake and (iv) they do not extract significant amounts of P that are not available to plants (Tiessen and Moir, 1993).

To assess the soil P available to crops, several extracting agents are being used with the most commonly utilised ones shown Table 2.4.

Table 2.4: Reagents commonly used for extraction of P available to crops in soils (Fageria *et al.*, 1997).

Extracting reagents	Soil/reagent ratio	Name of procedure
0.025N HCl + 0.03N NH_4F	1: 10	Bray 1
0.1N HCl + 0.03N NH_4F	1:17	Bray 2
0.5M $NaHCO_3$, pH 8.5	1: 20	Olsen
0.05N HCl + 0.025N H_2SO_4	1:4	Mehlich 1
0.2N CH_3COOH + 0.25N NH_4Cl + 0.015N NH_4F + 0.012N HCl	1:10	Mehlich 2
0.2N CH_3COOH + 0.25N NH_4Cl + 0.015N NH_4F + 0.013N $HN0_3$ + 0.001 MEDTA	1:10	Mehlich 3
0.002N H_2SO_4 buffered at pH 3 with $(NH_4)_2S0_4$	1:100	Truog
0.54N HOAc + 0.7 NaOAc, pH 4.8	1:10	Morgan
0.02N Ca-lactate + 0.02NHCl	1:20	Egner
1% citric acid	1:10	Citric acid

The extractants in Table 2.4 cover a broad range of soil conditions ranging from acid to alkaline, from low to high cation exchange capacity (CEC), and from arid to humid soil conditions (Fageria *et al.*, 1997). Many of the soil test extractants employ acids to dissolve the Ca, Al, and Fe phosphates, which have been shown to be the main inorganic sources of labile P (Beegle, 2005). Extractants such as the Bray-1 and -2, and Mehlich-1 and -3, are dilute solutions of the strong acids, namely HCl, HNO_3, and H_2SO_4. As discussed by Holford (1997), a soil test should extract a quantity of P that is positively related to

exchangeable P and negatively related to the P buffering capacity of the soil but in practice the selection of the extractant is based on the degree of correlation between the soil P extracted and a measure of crop growth (Fageria *et al.*, 1997). The preferred extractant is normally the one giving the best correlation between the soil P extracted and the measure of crop growth used.

The test based on Bray-1 extractant, which is a mild-acid solution, has been found to be reliable for the prediction of crop response to P fertilisation on neutral to acidic soils but it has been less effective on alkaline soils, where the acid from the extractant is neutralised quickly by the bases present while the fluoride ions are precipitated by Ca (Sanchez, 2007). The Bray-2 extractant has the same concentration of NH_4F (0.03M) as Bray-1, but the HCl concentration has been raised to 0.1M to give it an increased capacity to extract the less soluble Ca-P (Fageria *et al.*, 1997).

The Mehlich-1 soil-test extractant has the advantage of simultaneously extracting P, K, Ca, Mg, Cu, Mn, Fe, and Zn (Sanchez, 2007). The Mehlich-2 extractant was developed to allow simultaneous determination of the same nutrients over a still wider range of soil properties (Sanchez, 2007). However, the corrosive nature of the Mehlich-2 extractant discouraged its use and its composition was ultimately slightly modified to become Mehlich-3 which has been found to be reliable across a wide range of soil-crop production circumstances (Sanchez, 2007). While a vast majority of soil testing laboratories use the extractants listed in Table 2.4, other alternative soil P tests have been utilised and they include water-extractable P, 0.01M $CaCl_2$ extractable P, resin-extractable P and iron oxide strip extractable P (Beegle, 2005).

Whichever extractant or method is selected for the available soil P analyses, the P soil-test levels need to be converted into P fertiliser recommendations. A useful starting point for that conversion is the determination of critical P soil-test levels, which refer to the soil P value above which there will be no response to P fertiliser (Sanchez, 2007). In fact, to convert soil test P values into fertiliser P recommendations two sets of calibration information for each combination of crop-soil type-climate are required, namely: (i) the

soil P test level that produces the maximum yield, and (ii) the quantity of fertiliser P that is required to reach that test level (Thomas and Peaslee, 1973). Thus, in situations where the soil test P levels are below the critical P value, fertilisation is required and the rate of P fertiliser will depend on the soil-test P.

2.6 Management of agricultural P for environmental protection

In general, P in agro-ecosystems must be managed to ensure adequate P availability for optimum crop production and to minimise losses of P that could negatively impact water quality (Bundy *et al.*, 2005). Fresh water eutrophication is often accelerated by increased P inputs, a greater share of which comes today from agricultural non-point sources than two decades ago (Sharpley and Withers, 1994). As outlined by Sharpley *et al.* (1993), the main factors controlling P movement in a landscape are, as illustrated in Figure 2.6, the transport and P source factors. Transport factors refer to the mechanisms by which P moves within a landscape and include runoff and erosion. The factors which influence the source and amount of P available to be transported are soil P content, the rate and method of P application and whether P is applied as mineral fertilisers or in organic forms (Sharpley *et al.*, 1993).

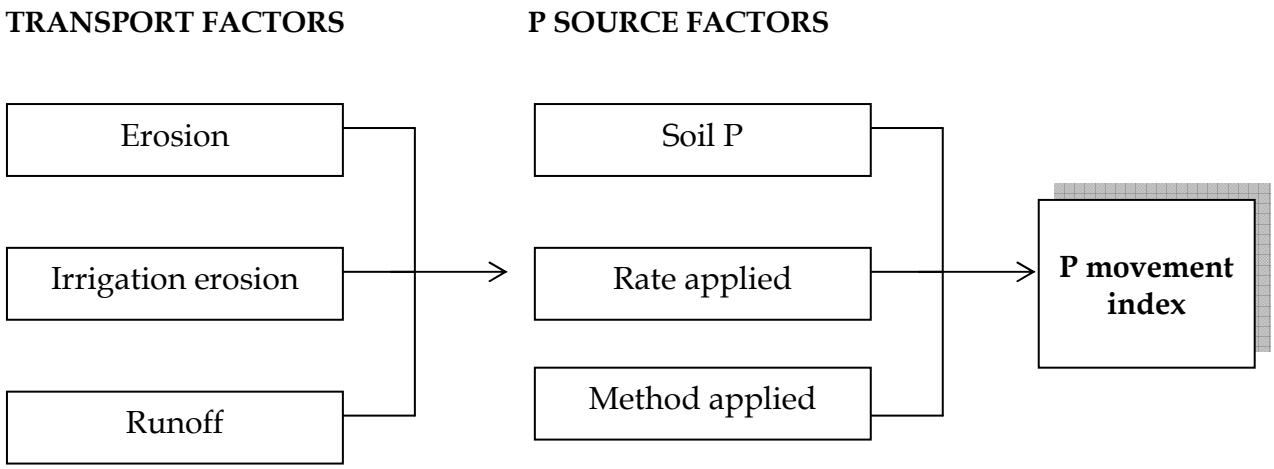


Figure 2.6: Transport and P source factors involved in P movement across the landscape (Sharpley *et al.*, 1993).

Phosphorus movement across landscapes can be reduced by careful fertiliser P management and by controlling erosion and runoff (Sharpley *et al.*, 1993). Subsurface placement of P away from the zone of removal in runoff will, according to Sharpley *et al.* (1993), reduce the potential for P movement. The proper management of organic P sources should be ascertained including its careful timing and rate of application. Environmental concern has in effect forced many states in the United States to consider the development of recommendations for manure applications based on the potential for P loss in runoff, as well as on the crop N and P requirements (Sharpley *et al.*, 1996). Other possible options for efficient utilisation of manure have included basing application rates on site susceptibility to runoff (Sharpley and Withers, 1994).

Phosphorus loss via erosion and runoff may be reduced by conservation tillage, crop residue management, buffer strips, riparian zones, terracing, contour tillage, cover crops, and impoundments or small reservoirs (Daniel *et al.*, 1998). While conservation tillage may reduce erosion in runoff compared to conventional tillage, it can on the other hand enhance leaching losses of nutrients (Sharpley and Withers, 1994). Furthermore efficient irrigation, particularly furrow irrigation, may reduce P loss by minimising induced runoff and erosion (Sharpley and Withers, 1994).

Soil P tests have so far provided farmers with an indication of how much P is available to crops in a soil (Sharpley and Withers, 1994). The review of literature has shown that little use is being made of soil tests for managing P in soil for protection of freshwater sources. There is no valid scientific reason why simple soil P tests that are currently being used cannot be extended to identify not only agronomically P-deficient soils, but also those that are, from an environmental viewpoint excessive in P.

2.7 Conclusions

The review of the literature has shown that growers today have a voluminous amount of information on P that they can rely upon to optimize crop production. Thus not only are the functions of P inside the plant well-defined and the visible symptoms of its deficiency in the field accurately described, the growers in addition have a clear understanding of the

merits and demerits of each P source, when and how to apply the P, how frequently and how much P should be used to achieve their production target. Indeed the review of the literature has shown that numerous soil P analysis methods exist to make soil P testing a regular and routine feature in agricultural crop production. A soil P test method can be proposed for any soil type or condition that may be encountered in the field.

However the review of the literature has also revealed that studies on the role of P as an environmental pollutant still lags behind the research that has been carried out on P in agricultural production. Admittedly, a lot of information is available on P as a contaminant of freshwater resources and on the management practices to minimise its pollutant potential but important gaps still persist, for instance, on the tools available to indicate with certainty when that important plant nutrient poses a problem to the environment. From this perspective, while many soil tests can be proposed to define the critical soil P level below which a deficiency to the crops is very likely to be encountered or above which P fertilisation will not be needed, soil tests that indicate what P level in soil will pose a risk to freshwater supplies are few. This study will contribute to narrow that gap in the existing knowledge by establishing after a review of the P fertiliser usage and P status of the soils in Mauritius, the level of P in sugarcane soils of Mauritius that is likely to pose a hazard to the natural freshwaters on the island.

3 Usage of P fertilisers and agronomic P status of soils in Mauritian sugarcane industry

3.1 Introduction

On account of its resilience to drought and to cyclone, sugarcane production is considered to be the only sustainable agricultural system in Mauritius, so much so that Mauritian agriculture has become synonymous with sugarcane production. Today out of the total land area of 186,500 hectares, sugarcane is cultivated on 69,000 hectares representing 80% of the arable land or 37% of the existing land in Mauritius as illustrated in Figure 3.1.

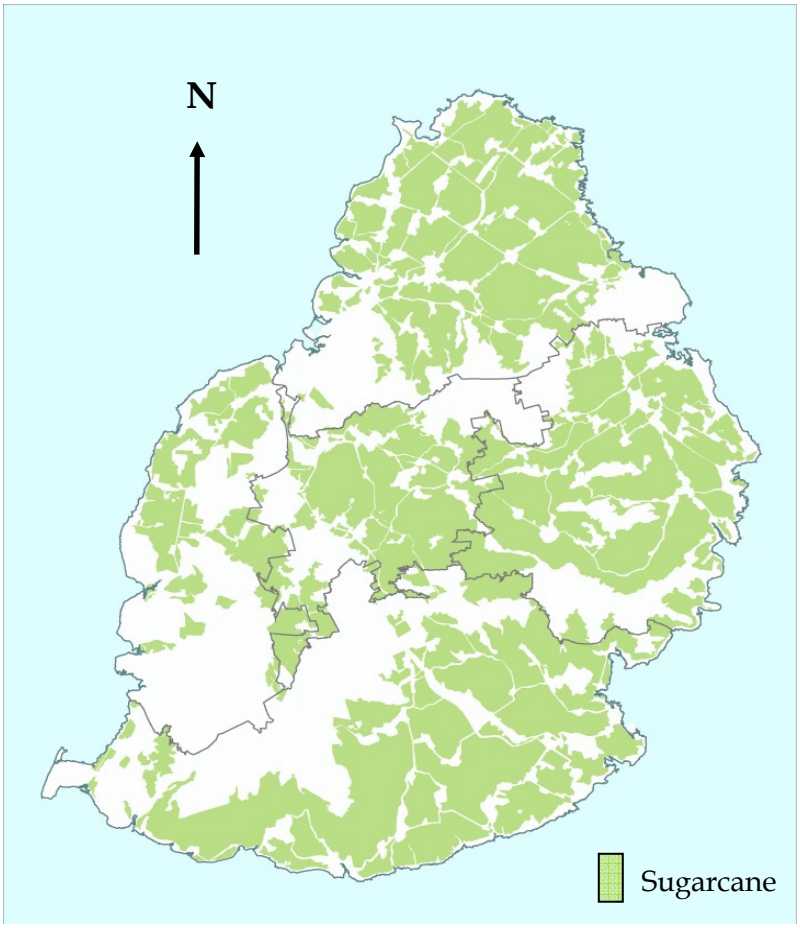


Figure 3.1: Land under sugarcane cultivation in Mauritius.

Sugar production varies from year to year depending on the vagaries of climate but on average approximately 520,000 tonnes are produced annually. Though climate and edaphic factors are conductive to good sugarcane growth in Mauritius, the success of

sugarcane production on the island can to a large extent be attributed to the adoption of good crop management practices (Ng Kee Kwong and Deville, 1987; 1992) including those that meet the nutrient needs of the crop. In this context, the importance of optimising P nutrition has long been recognised in the growth of sugarcane and as reviewed by Korndörfer (2005), P plays a key role in the metabolic processes during which a compound known as glucose-1-phosphate combines with fructose to form sucrose, the material of commercial importance in the cultivation of sugarcane. Of the three major fertiliser elements N, K and P, the latter as stated by Parish and Feillafé (1958) may have the least dramatic effects on the appearance of the sugarcane plants; yet in terms of yield it is just as vital as the other two major nutrients and when lacking can impose a limit to yields which no amount of N or K can overcome. This being the case, it goes without saying that P fertilisation is a regular feature in the management of the sugarcane crop in Mauritius.

This chapter reviews P fertiliser usage in sugarcane cultivation in Mauritius and the impact which repeated applications of the P have had on the P status of the soils in Mauritius. Information of this nature is essential for obtaining a better perspective on the potential threat of freshwater pollution by the Mauritian sugarcane industry.

3.2 Phosphorus fertiliser usage in Mauritius

3.2.1 Data processing and presentation

Phosphorus fertiliser consumption by the sugar industry was compiled from the fertiliser statistics published yearly by the Mauritius Chamber of Agriculture in its annual reports. The information so obtained on the amount and forms of each fertiliser procured by the industry was complemented or cross-checked with recorded fertiliser sales by the fertiliser importing companies namely, the Mauritius Chemical Fertiliser Industry and Island Fertilisers Limited which are the two main importers of fertiliser in Mauritius, controlling more than 90% of the market.

The amount of P_2O_5 (as well as N and K_2O) utilised annually by the sugar industry was obtained by multiplying the percentage nutrient in the fertiliser by the quantity (in tonnes)

of fertiliser applied in sugarcane fields. The calculations and graphical presentations of data were done using the Microsoft Excel 2003 program on Windows XP.

3.2.2 Historical trends in P fertiliser usage by the Mauritian sugar industry

The different types of fertilisers most commonly used by the Mauritian sugar industry are shown in Table 3.1.

Table 3.1: Fertilisers most commonly utilised by the sugar industry in Mauritius.

	% N	**% P_2O_5**	**%K_2O**	**Formula of main compound**
Straight fertilisers				
Rock phosphate	0	30	0	$Ca_3(PO_4)_2$
Guano phosphate	0	23	0	$Ca_3(PO_4)_2$
Single superphosphate	0	19	0	$Ca(H_2PO_4)_2$
Triple superphosphate	0	46	0	$Ca(H_2PO_4)_2$
Urea	46	0	0	$CO(NH_2)$
Calcium ammonium nitrate	26	0	0	$Ca\ (NO_3)_2.(NH_4NO_3)$
Potassium Chloride	0	0	60	KCl
Complex fertilisers				
Mono-ammonium phosphate	12	52	0	$NH_4H_2PO_4$
Di-ammonium phosphate	18	46	0	$(NH_4)_2H_2PO_4$
17-2-27	17	2	27	-
17-8-25	17	8	25	-
16-22-22	16	22	22	-
13-20-20	13	20	20	-
18-0-24	18	0	24	-
By-products of sugar industry used as fertiliser				
Concentrated molasses stillage	0.6	0.2	5.0	-
Vinasse	0.3	0.1	1.6	-
Scums (Filter muds)	1.0	1.4	0.3	-

As can be anticipated, P fertiliser usage has been intimately linked to the intensive cultivation of sugarcane which inevitably implies relatively high inputs of not only P fertilisers, but of N and K fertilisers as well. In fact as the aim is to achieve and sustain a high level of sugarcane production in Mauritius through elimination of all limiting factors to growth, including nutrients, P fertiliser usage in sugarcane in Mauritius cannot be dissociated from that of N and K. Routine applications of the three major nutrients to soils has therefore become standard practice in Mauritius. Other elements (e.g. Ca, Mg, S) are just as vital for normal plant cane growth as the three major ones, but their supply in Mauritian soils is considered sufficient to meet the needs of the sugarcane crop. It is moreover believed that they do not have any bearing on the economics of sugar production; rather deficiencies of N, P and K must be completely corrected before any possible limiting effects of the other essential nutrients on yields can be considered (Parish and Feillafé, 1958).

The five yearly averages of fertiliser N, P and K (in terms of N, P_2O_5 and K_2O respectively) usage in sugarcane in Mauritius since the beginning of the 20th century are shown in Figure 3.2. As can be seen NPK fertiliser consumption in sugarcane cultivation closely matches sugar production in Mauritius. It can be stated that during the first half of the 20th century, the sugar planting community were generally not concerned about P fertilisation and its importance in enhancing crop yields. Among the possible causes for neglecting P fertilisation during that period, as mentionned by Parish and Feillafé (1959), was the fact that with the introduction of higher yielding cane varieties, sugar production had increased to mask the deleterious effect of P deficiency on yields. The levels of mineral fertilisers consumed were then fairly low with an average of 2,120 tonnes of N, 790 tonnes of P_2O_5 and 1,170 tonnes of K_2O. Import of N was the highest representing approximately twice the amount of K_2O imported and about three times that of P_2O_5. This can be explained by the fact that K was supplied to sugarcane by molasses while P was added by scums. Molasses and scums (also known as filter muds) were at that period considered as wastes from sugar manufacturing processes.

Scums are obtained during the clarification of sugarcane juice with lime and contain on average about 2% P_2O_5 on a dry matter basis (Parish, 1964). Molasses on the other hand is obtained during the evaporation and crystallisation process and contains on average 5% K_2O on a fresh weight basis. The application of these wastes was often believed to be sufficient in meeting the P and K requirements of the sugarcane plant. Moreover as the effect of N on a growing crop is so marked visually, there has never been the slightest hesitation by the planting community to accept N as the king-pin of a fertilisation programme. The symptoms of deficiency of K and P being less spectacular than with N, sugarcane planters had a tendency to underfertilise their fields with P and K and overfertilise them with N.

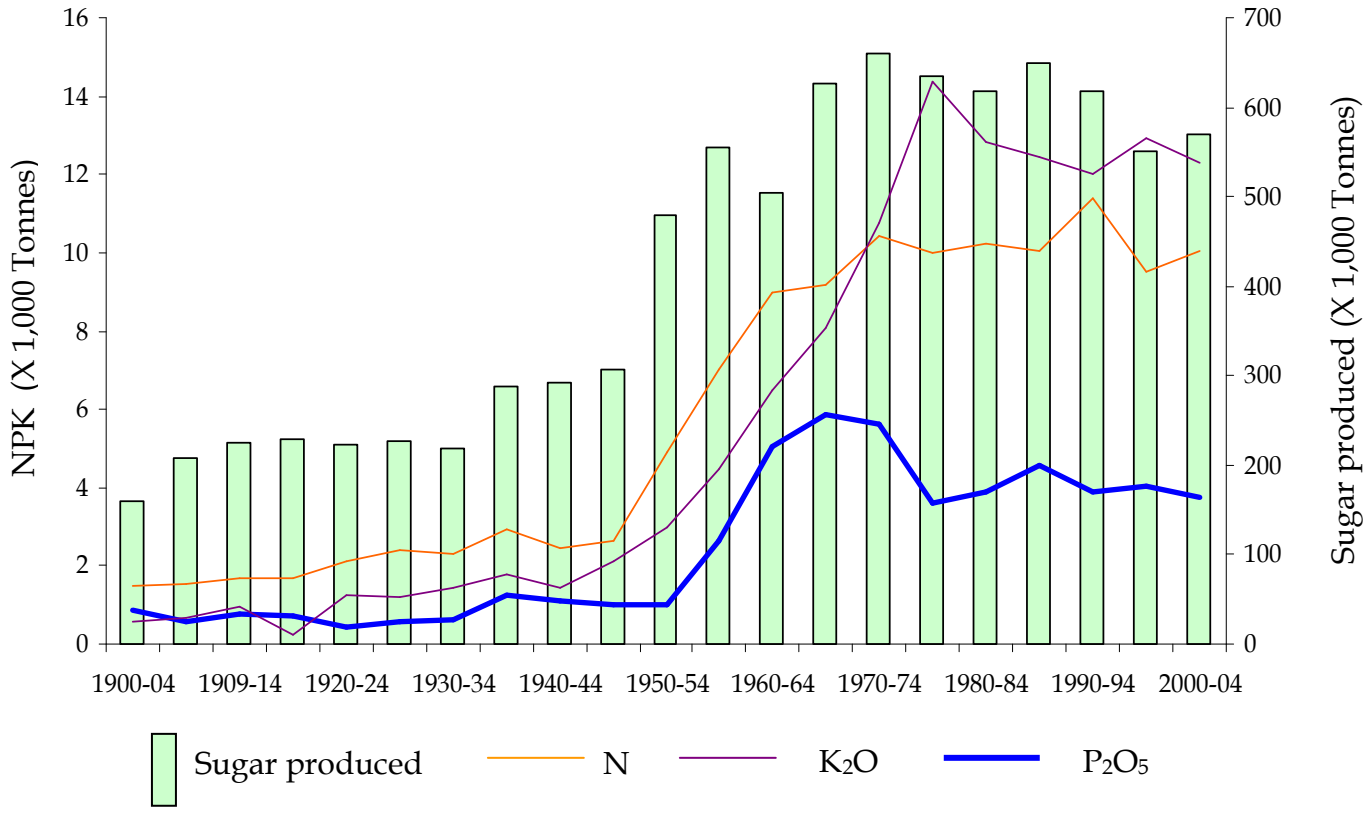


Figure 3.2: Five yearly averages of sugar production and of NPK usage in sugarcane in Mauritius from 1900 to 2004.

During the second half of the 20th century, NPK fertiliser consumption experienced a boom which was accompanied by a similarly sharp increase in sugar production (Figure

3.2). The peak in sugar production was reached in the 1970s when NPK fertiliser usage was at its maximum. The rise in sugar production is explained not only by the sharp increase in the quantity of fertilisers used but also by the rise in sugarcane area during that period as shown in Figure 3.3. Concomitantly the boom in NPK fertiliser consumption can also be attributed to the expansion in area under sugarcane.

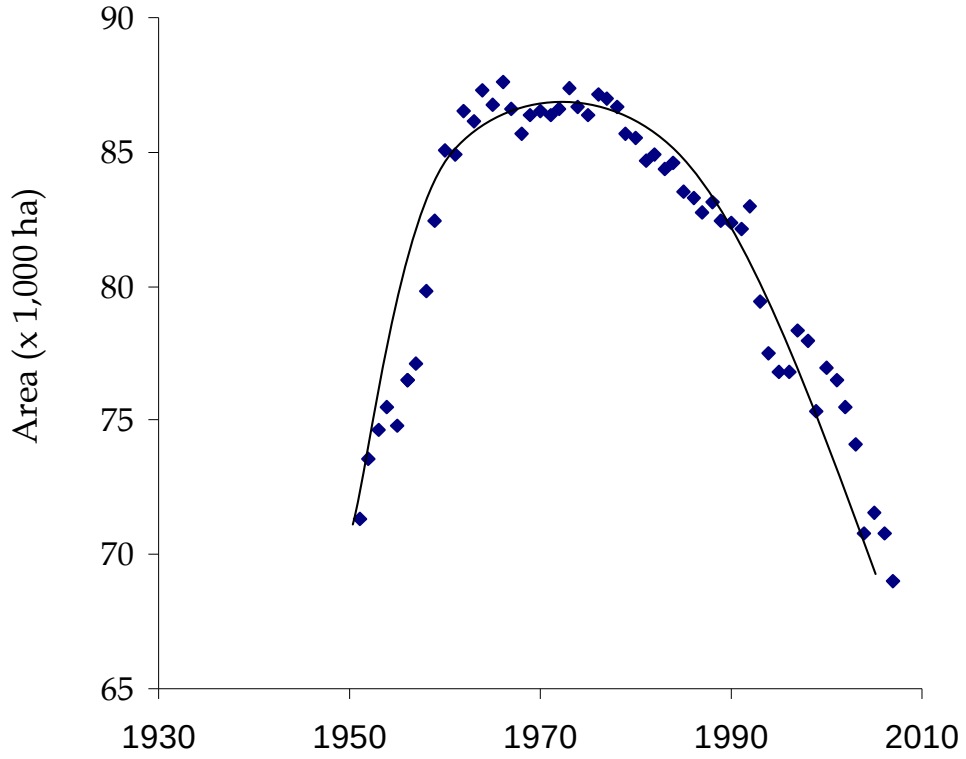


Figure 3.3: Evolution in area under sugarcane in Mauritius since 1951.

Usage of P fertiliser in the 1950s was given a further boost when large areas of ratoon and even virgin cane showed the typical discoloration of P deficiency and yearly foliar diagnosis data were showing a worsening P status of the Mauritian cane lands (Parish, 1964). It was established that about 30% of the sugarcane lands in Mauritius were deficient in P and P fertilisation became recognised then as being essential for maintaining a viable sugar industry. As a consequence, from the period 1955 to 1970, P imports as shown in Figure 3.2 increased from 570 tonnes to 5,675 tonnes indicating clearly that a big effort was made to replenish P reserves of soil.

However since the late 1970s fertiliser P consumption by the sugar industry has shown a tendency to decline, not because the soil P status has improved to the point that P fertilisation could be lowered but mainly as a result of the decrease in land area under sugarcane (Figure 3.3). Another point of relevance in Figure 3.2 is the fact that consumption of K_2O as from the 1980s exceeded that of N used by the sugar industry. The reason behind this is that the planting community became conscious from trials on K response by sugarcane that as opposed to an uptake of only 150 kg N ha^{-1}, as much as 300 kg K_2O ha^{-1} may be removed from the soil by an average sugarcane crop (Anon, 1994). Consumption of P fertilisers by the sugarcane industry has always remained below that of N because on average only 60 kg P_2O_5 ha^{-1} is removed by an average crop of sugarcane.

Compilation of the NPK fertiliser usage has shown that on average 9,200 tonnes N, 3,350 tonnes of P_2O_5 and 9,350 tonnes of K_2O were applied annually to sugarcane during the period 2005 to 2008. It is unlikely that the use of NPK fertilisers will decline further in the foreseeable future. Indeed the rising population and the continuing expansion of the tourist industry are increasing the demand for food. This coupled with the scarcity of new lands for agricultural production, is expected to lead to even more intensive use of sugarcane rotational lands and interrows for food crop production. In consequence, the consumption of P as well as N and K fertilisers is more likely to rise in the short and medium future.

3.2.3 Types of P fertilisers used in sugarcane production

During the first 50 years of the 20th century, insoluble mineral P in the form of guano phosphate was the predominant if not the only form of mineral P fertiliser used in Mauritius, mainly because it was a cheap source of P that was obtained from the coral islands and atolls in the South West Indian Ocean, several of which belong to Mauritius (Parish *et al.*, 1956). It was a common practice at that time to mix guano phosphates with farmyard manure before application at planting.

Indeed organic fertilisers in the form of farmyard manure and scums were also disposed of in the fields during the early years of the 20th century. As the scums contained on

average only about 2% P_2O_5 on a dry matter basis and their utilisation required considerable transport to the fields (Parish, 1964), the tendency then was that areas close to the sugar factories received scums whilst outlying fields did not receive this P supplement. This eventually resulted in the build-up of soil P in areas near the factories receiving massive dressings of scums (Parish and Feillafé, 1959). It is also important to add that apart from providing P, scums promote significant changes in the soil chemical attributes, such as an increase in Ca and N availability, increased organic carbon content and CEC, a decreased exchangeable Al and an improvement in soil texture (Korndörfer, 2005). It is still a recommended agricultural practice to apply scums at planting of the sugarcane.

As no guidance was available to indicate the optimum level and types of P fertilisers best suited for Mauritius, experiments were initiated in 1954 to test the efficacy of various forms of P fertilisers (Parish *et al.*, 1956). The results showed that water soluble phosphates such as superphosphates were superior to the various forms of insoluble mineral fertilisers, at that time often referred to as tri-calcium phosphates [$Ca_3(PO_4)_2$]. Other field experimentation set up to develop a rational and economic P fertilisation programme for sugarcane showed that for the plant cane, the water-soluble forms of P were superior to insoluble phosphates such as guano and rock phosphates, particularly when soil pH was above 6.0 (Anon, 1964). However in ratoon crops, guano phosphates were found to be as good as the soluble forms of P especially in acid soils (Parish and Feillafé, 1959). These studies promoted the utilisation of water soluble forms of P fertilisers which at that time were available as superphosphates.

Consequently as shown in Figure 3.4, the amount of superphosphates used in sugarcane rose as from the 1960s and that rise lasted until the late 1980s. During that time span usage of guano/rock phosphates declined. Substitutions of the guano/rock phosphates by superphosphates by the sugarcane planting community had thus been a slow process. The growers were reluctant to change to the water soluble P fertilisers because the guano/rock phosphates were relatively cheap as compared to the water soluble P fertilisers. Indeed, during the early 1960s, guano/rock phosphates cost on average MUR 0.60 per kg P_2O_5

while triple superphosphate was sold on average at MUR 1.12 per kg P_2O_5, that is approximately twice the price of P_2O_5 in guano/rock phosphates. It is to be noted from Figure 3.4 that while in 1966, guano/rock phosphate accounted for 40% of the P_2O_5 utilised by the sugar industry it had decreased to 9% in the late 1980s. Eventually in the early 1990s insoluble phosphates were no longer utilised, because the local market for the guano/rock phosphates had shrunk to the extent that it was too small to be of interest to the importers of that commodity.

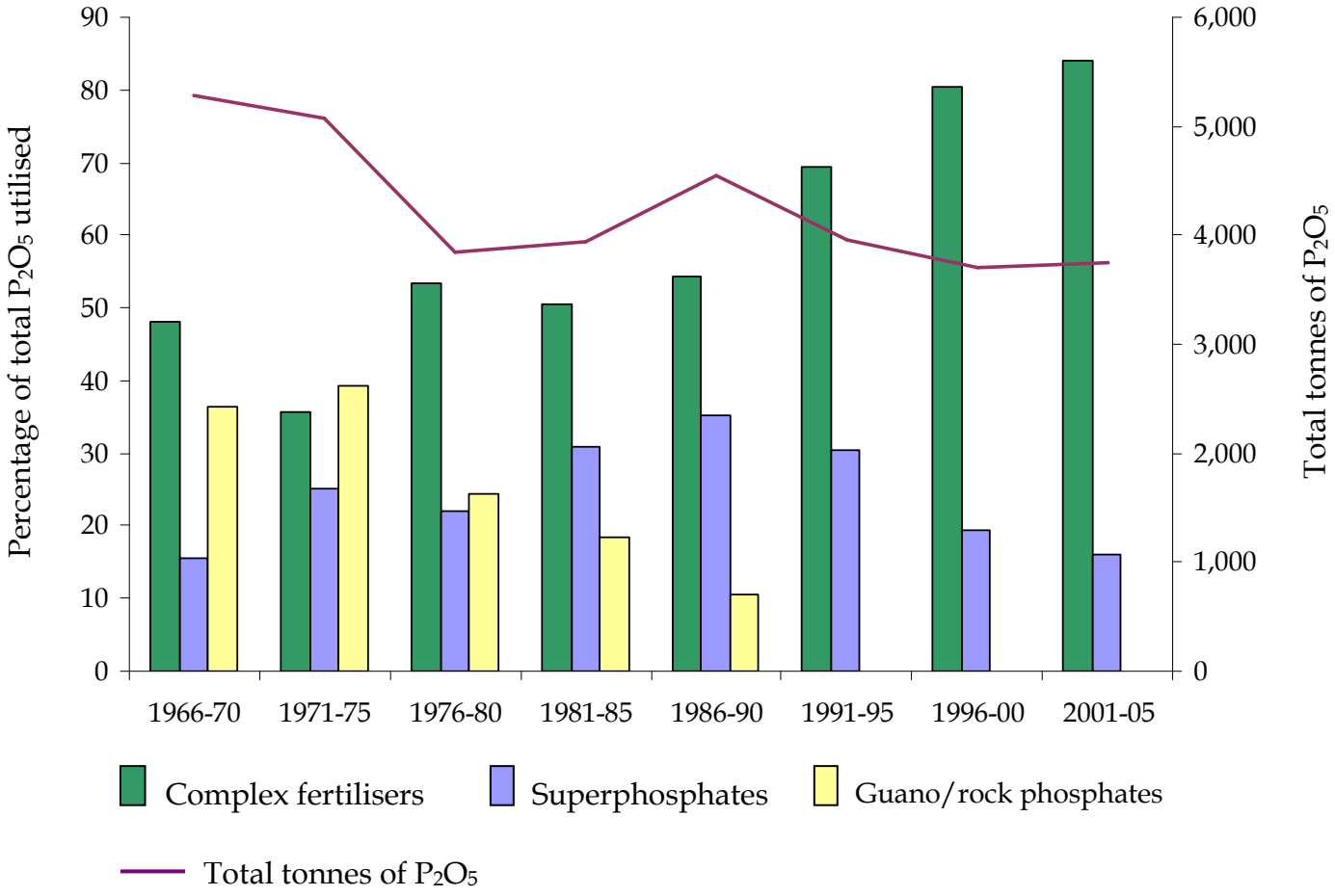


Figure 3.4: Types of P fertilisers utilised from 1966 to 2005.

The cost of unit nutrient in the fertiliser has invariably always been the determining factor in the choice of the fertiliser for application to sugarcane in Mauritius. As indicated in the preceding paragraph, guano/rock phosphates had in the past been preferred to superphosphates on account of their lower unit price of P_2O_5. Likewise granulated

complex fertilisers, as shown in Figure 3.4, became the preferred source of P for sugarcane in the late 1970s because the price per unit P_2O_5 was lower than in the straight fertilisers.

Research findings also played a significant role as from the early 1980s, in accentuating the choice of complex fertilisers as a P source for sugarcane. As shown in Figure 3.4, complex fertilisers, which accounted for only 48% of the total P utilised in the 1960s and 1970s, supplied, as from the 1990s, some 80% of the P_2O_5 used in sugarcane. Prior to the mid 1980s, straight fertilisers such as triple superphosphates and ammonium sulphate were recommended in plant cane on the premise that P is immobile and is best applied at planting while N is so mobile in soils that its application should be delayed until eight weeks after planting to allow the sugarcane to develop a sufficiently extensive root system to absorb the N. Studies using ^{15}N-labelled fertiliser having, in the 1980s, indicated that leaching of fertiliser N in soils of Mauritius is insignificant and field trials having also shown that yields of plant cane showed no significant difference when complex (applied at planting) instead of straight fertilisers (P and K at planting, N eight weeks after) were used, there was no longer any justification for not adopting complex fertiliser for plant cane (Ng Kee Kwong and Deville, 1984). As a result, the use of complex fertilisers rose steeply as from 1986 before plateauing in the mid 1990s (Figure 3.4). Concomitantly, the amount of superphosphates, which attained a peak of 35% in the mid 1980s, gradually decreased as their use became confined to correcting P deficiencies when diagnosed by foliar diagnosis in ratoon canes.

3.3 Phosphorus status of soils under sugarcane in Mauritius

3.3.1 Geology, climate and soils of Mauritius

Except for the coral reefs, beaches or dune sands fringing the greater part of the coastline, Mauritius is entirely volcanic in origin, originating from two main phases of volcanic activity, namely an *Older volcanic series* dating back 5 to 8 million years ago and a *Younger volcanic series* starting 3.5 million years ago (Arlidge and Wong, 1975). The remnants of the basaltic lavas of the Older Volcanic Series now stand as a discontinuous ring of mountain ranges and isolated peaks (Figure 3.5) rising 600 m to 900 m above sea level. They enclose a Central Tableland created by volcanic eruptions during the period of the Younger

Volcanic Series, particularly from the lava flows dating from 0.7 to 0.2 million years ago (Intermediate and Late Lavas). Except in the southwest part of the island, the mountain ranges are surrounded by the flat to gently undulating Coastal Plains resulting from outpourings of the Intermediate and Late Lavas with the latest lava flows occurring in the east at Plaine des Roches very recently in geological time (< 25,000 years).

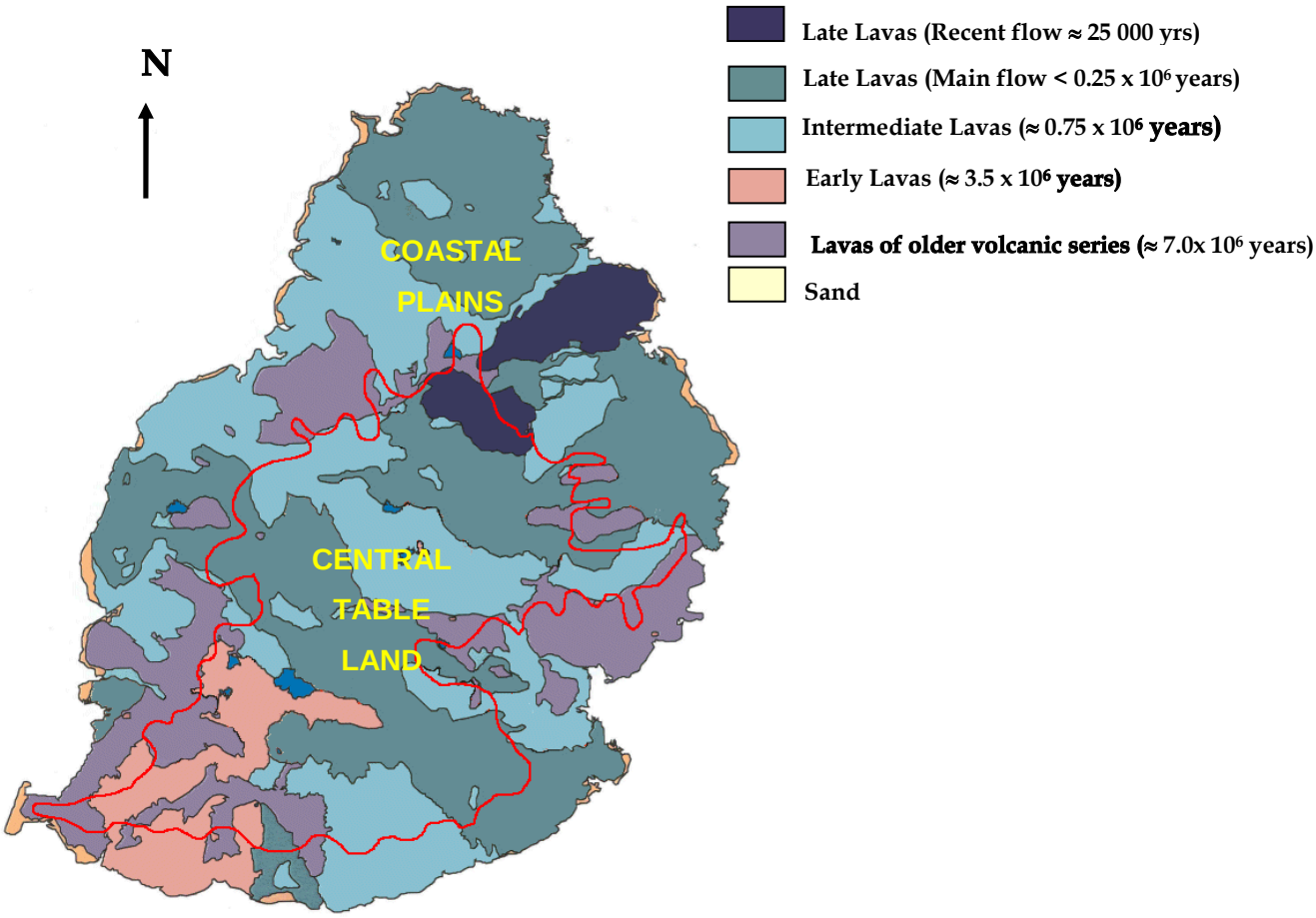


Figure 3.5: Geology of Mauritius.

On account of variations in wind exposure, altitude and distance from the sea, there exists a succession of climates. On the basis of Thornthwaite classification which places emphasis on the factor of evapotranspiration, a total of 24 different micro-climates have been differentiated in Mauritius (Halais and Davy, 1969). In general, however, the climate may be considered to comprise two seasons, namely a subtropical winter from May to October during which the island experiences a cool and comparatively dry season, and a

tropical summer from November to April which is warm and wet and often affected by tropical cyclones (Padya, 1989). July is the coolest month with mean temperatures of 21°C in the coastal regions and 16.5°C in the Central Tableland at an elevation of about 600 m. February is generally the warmest month with corresponding mean temperatures of 27.8°C and 22.3°C, the difference in the mean temperatures between the two months of July and February being only 5.5°C.

Mean annual rainfall changes abruptly from 800 mm on the west coast to over 4,000 mm in the Central Tableland over a distance of only 20 km. From May to October rainfall expressed as a percentage of annual rainfall varies from 30 to 35% in locations exposed to the southeast trade winds and between 10 and 30% in the western leeward areas. The uneven distribution and frequency of rainfall coupled with high rates of evaporation (1,870 mm annually in the northern and western coastal areas and about 1,379 mm annually in the highest parts of the island) give rise to a moisture deficit of moderate to severe degree and sustained sugarcane production is not possible without irrigation on the Coastal Plains.

It is against the climatic background described above that the soils of Mauritius have developed from basic volcanic rocks, mostly olivine basaltic lavas, of very different ages. However, agriculturally important soils of Mauritius can be classified into two main groups only, namely (a) the typical *mature ferratillic soils* or *latosols* in which the decomposition of the parent basaltic lava rock has proceeded to such an extent that, except for large rounded boulders and stones, there are now no undecomposed minerals in the soil complex, and (b) the typical *immature latosolic soils*, the properties of which are affected by the presence of minerals still in the process of weathering and which, in the field, are characterized by the presence of more or less high proportions of angular stones and gravels of vesicular lava.

Mauritius in fact provides a very fine example of zonality of soils, that is, the progressive intensity of weathering and soil development with increase in the intensity of soil forming factors, notably rainfall. Using a genetic classification adopted for the soil survey of

Hawaii and on the basis of differences in rainfall and age of parent material, 13 soil types as shown in Figure 3.6, have been recognized with subdivision at a lower category into families (Parish and Feillafé, 1965).

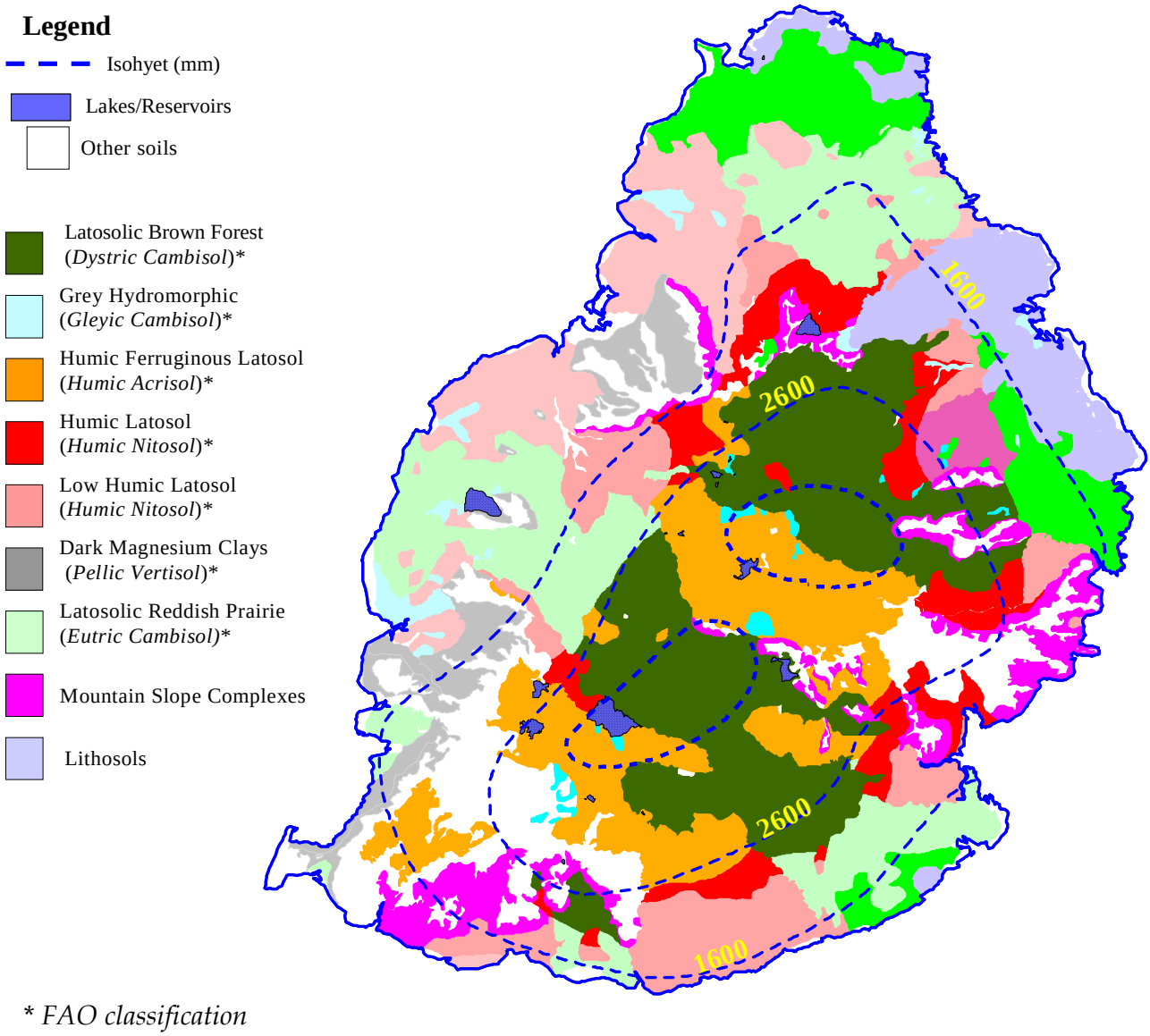


Figure 3.6: The different soil types in Mauritius according to Parish and Feillafé (1965).

However, as shown in Table 3.2, only five soil types, namely the *Low Humic Latosols*, *Humic Latosols*, *Humic Ferruginous Latosols*, *Latosolic Reddish Prairie* and *Latosolic Brown*

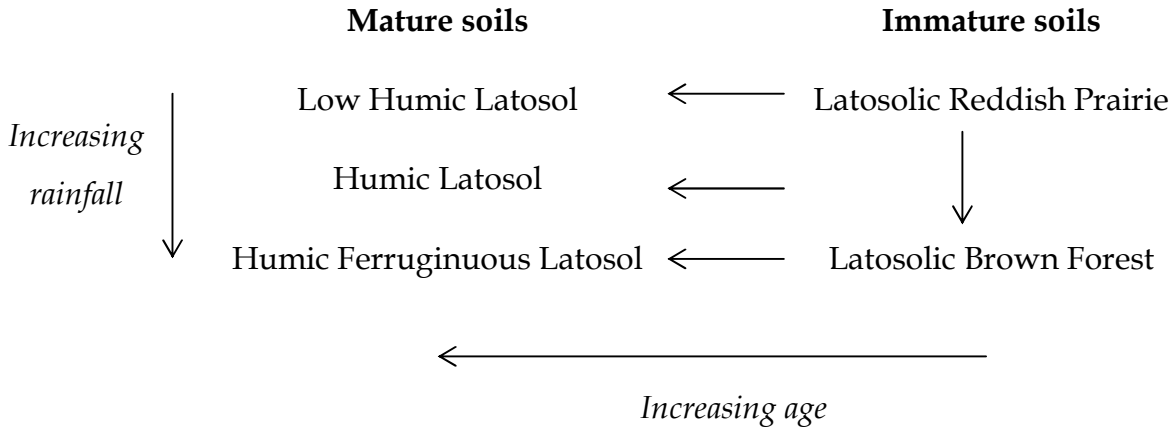
Forest account for nearly 90% of the agricultural lands in Mauritius under sugarcane cultivation.

Table 3.2: Sugarcane land area under each soil group in Mauritius.

Soil group	Sugarcane land area (hectares)
Low Humic Latosol (*Humic Nitosol*)*	16, 289
Humic Latosol (*Humic Nitosol*)*	6,032
Humic Ferruginous Latosol (*Humic Acrisol*)*	7,668
Latosolic Reddish Prairie (*Eutric Cambisol)**	18,174
Latosolic Brown Forest (*Dystric Cambisol*)*	12,694
Grey Hydromorphic (*Gleyic Cambisol*)*	833
Dark Magnesium Clays (*Pellic Vertisol*)*	549
Mountain Slope Complexes	3,487
Lithosols	3,499
Coral Soil	102
Total land area (hectares)	**69,327**

* Soil group as per FAO classification (Arlidge and Wong You Cheong, 1975).

According to Parish and Feillafé (1965), the interrelationships among the five main soil types may be illustrated as follows:



A brief description of the five main soil types under sugarcane in Mauritius can be given as follows:

The *Low Humic Latosols* have developed on the Intermediate Lavas (Figure 3.5) and they occur in zones receiving 800 mm to 2,750 mm rainfall per year. Because the clay fraction in the soil is composed of kaolinite cemented with oxides, they have, in the field, the texture of silty clays or silty clay loams (Parish and Feillafé, 1965). A characteristic feature of this soil type, which covers 16.4% of the whole island, is the presence of manganese dioxide in the profile.

The *Humic Latosols* occur in the humid and superhumid zones with a mean annual rainfall ranging from 1,500 mm to 3,750 mm. This soil group, covering 5.2% of the island, is in fact, a transitional group between the Low Humic Latosol, in the low rainfall zone and the Humic Ferrigunous Latosol in the high rainfall regions (Parish and Feillafé, 1965). The clay fraction of the Humic Latosols consists mainly of more or less equal proportions of kaolinite, goethite and gibbsite.

The *Humic Ferrigunous Latosols* are the strongly weathered soils occurring in regions which receive between 2,500 mm to over 5,000 mm rainfall annually (Parish and Feillafé, 1965). This soil group which covers 11.4% of the whole island, is highly leached to the extent that its mineralogy is dominated by goethite and gibbsite.

The *Latosolic Reddish Prairie* and the *Latosolic Brown Forest* soils are the immature intrazonal soils developed from the late lavas under conditions where the effects of climate and vegetation had been masked by local factors of environment such as relief, drainage and age of the parent material (Parish and Feillafé, 1965).

The *Latosolic Reddish Prairie* soils which cover 19.9% of the island, occur in the dry areas (same rainfall zone as the Low Humic Latosol) but are also slightly acid to neutral in reaction. The *Latosolic Brown Forest* soils cover 16.5% of the island and have on the other

hand been formed in the super-humid area where Humic Ferrigunous Latosols are also encountered.

3.3.2 Ownership of land under sugarcane

The land under sugarcane in Mauritius is owned by some 20 miller/corporate planters (henceforth termed *large planters*) and some 25,335 independent growers (henceforth referred to as *small planters*). Sugarcane plantations attached to the large planters under the five main soil types cover a land area of around 41,906 hectares while 18,951 hectares of sugarcane land are occupied by small planters (Table 3.3).

Table 3.3: Distribution of the sugarcane land among the five main soil types of Mauritius and by planter category.

	Land area under sugarcane (hectares)	
Soil group	**Small planters**	**Large planters**
Low Humic Latosol (*Humic Nitosol*)*	4,037	12,252
Humic Latosol (*Humic Nitosol*)*	1,132	4,900
Humic Ferruginous Latosol (*Humic Acrisol*)*	2,154	5,514
Latosolic Reddish Prairie (*Eutric Cambisol)**	5,508	12,666
Latosolic Brown Forest (*Dystric Cambisol*)*	6,120	6,574
Total land area (hectares)	**18,951**	**41,906**

* Soil group as per FAO classification (Arlidge and Wong You Cheong, 1975).

The sugarcane fields owned by the large planters vary in size ranging from 750 to 5,500 hectares, and attain cane yields of up to 90 t ha^{-1}. They account for around 60% of the total sugar production in Mauritius. The 25,335 small planters hold a total of some 19,000 hectares made up of some 210,000 plots which vary in size from less than 0.1 to over 400

hectares. The majority (92%) of the small planters however hold less than two hectares each and their productivity is about 25% less than that of the large planters.

Though more of the small planters' land is located in the northern half of the island than in the south, the sugarcane fields of the large and small planters' generally lie side by side throughout the island (Figure 3.7). As a result, the difference in productivity between small planters and large planters cannot be attributed to differences in climate and soil types but rather in their management of the sugarcane plantations.

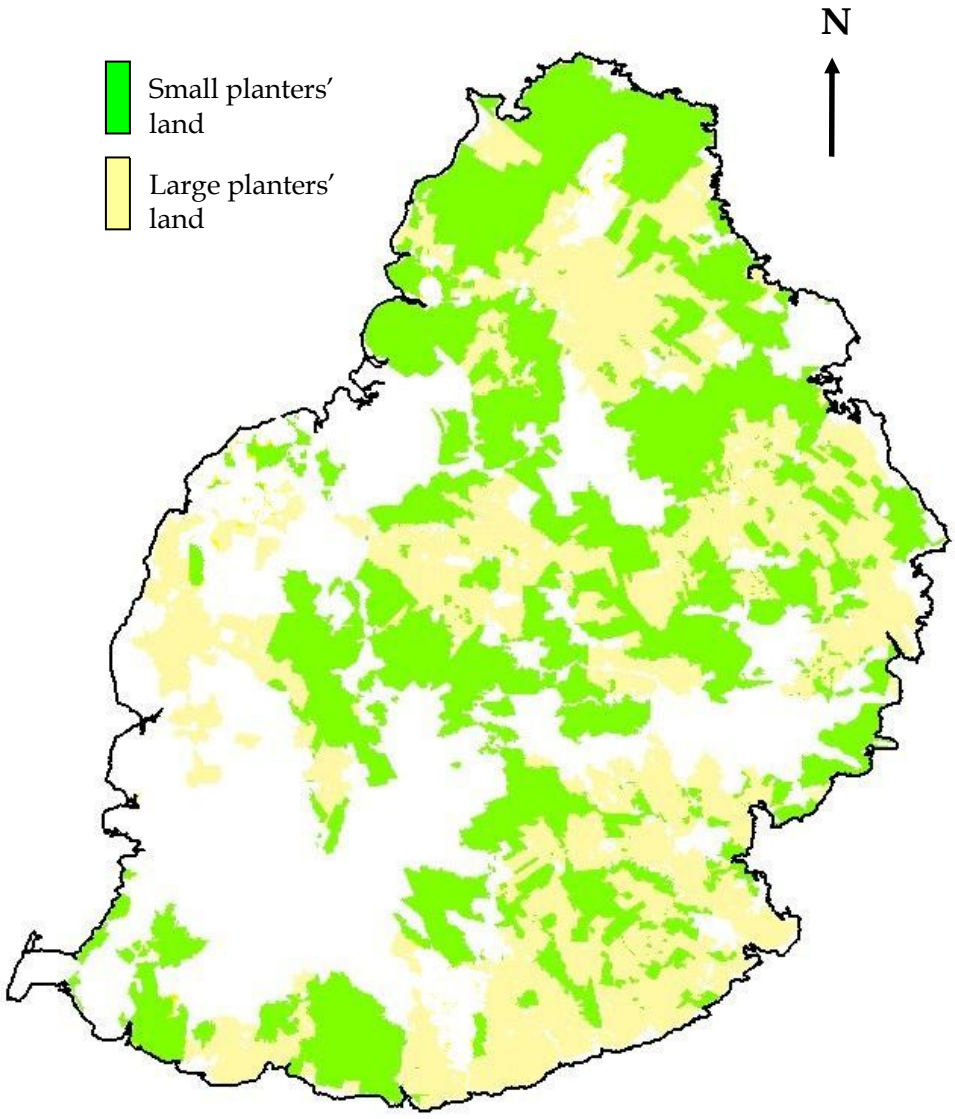


Figure 3.7: Distribution of sugarcane land among small and large planters.

3.3.3 Evaluation of P status of soils under sugarcane

3.3.3.1 Soil testing

The present method adopted in Mauritius to assess P available to sugarcane in soils of Mauritius utilises sulphuric acid (H_2SO_4) at a concentration of 0.1M. Several extractants have, however, been tried and used in the past. In the 1960s, a modified Truog method (0.01M H_2SO_4 containing 3g $[NH_4]_2SO_4$ L^{-1}) was used to estimate available P in the sugarcane soils of Mauritius. Studies carried out by Parish *et al.* (1966) subsequently showed that the statistical correlation was poor between the available P determined by the modified Truog extractant and leaf P levels in sugarcane growing in the latosols. The modified Truog's method with 0.01M H_2SO_4 as extractant moreover failed in numerous instances to accurately predict the agronomic P status of soils in Mauritius (Cavalot *et al.*, 1988). The method apart from being soil-pH dependent frequently underestimated the available P to sugarcane in soils (Anon, 1983). Thus soils which were tested to be deficient in P failed to respond to P fertiliser applications.

The best correlation with leaf P levels for all soil groups combined was found with the Saunder's extractant (0.1M NaOH). As a consequence, both the modified Truog's (using acid extractant) and Saunder's (using alkali extractant) methods were utilised simultaneously to assess the agronomic soil P status. Additional data such as soil pH (KCl) and soil groups, which were differentiated into free and rocky (or gravely) soils were also included in the interpretation of the soil test P values and in the formulation of fertiliser P recommendations. Furthermore to have more accurate interpretation of the soil test P results, soil sampling was done to obtain three composite soil samples which were analysed separately and the mean values taken to be representative of the field (Halais *et al.*, 1967).

Studies carried out later on soil P mineral fractions showed that the P supply to sugarcane comes collectively from both Ca-P and Al-P components (Wong You Cheong and Parish, 1968). The significance of soil organic P in the nutrition of sugarcane in Mauritius was found to be of far less importance than that of the inorganic P even though it constitutes

about 21 to 38% of the total P in soils (Anon, 1986). With the recognition of the Al-P as a major source of available P in soils of Mauritius, it was hypothesized that the availability of P to sugarcane should best be evaluated by an acid extractant capable of solubilising both the Al-P and Ca-P. This was achieved by simultaneously raising the concentration of H_2SO_4 to 0.1M and reducing the extractant to soil ratio from 100:1 to 50:1 (Cavalot *et al.*, 1988).

The method using 0.1M H_2SO_4 as an extractant had since been validated by field experimental data which also provided the basis for interpreting and formulating fertiliser recommendations at planting (Table 3.4). It is currently being utilised as a routine soil test in the agronomic P management of soils under sugarcane in Mauritius. As shown in Table 3.4 fertiliser P is not recommended to sugarcane in soils with more than 80 mg P kg^{-1}.

Table 3.4: Phosphorus fertiliser recommendations to sugarcane in Mauritius based on soil P test values (Cavalot *et al.*, 1988).

Soil test value *0.1M H_2SO_4-P (mg kg^{-1})*	**kg P_2O_5 ha^{-1} to apply** *(to raise soil P to 80 mg kg^{-1})*
30	600
35	525
40	475
45	425
50	375
55	325
60	275
65	200
70	125
75	50
80	0

3.3.3.2 Foliar diagnosis

As reviewed by Ng Kee Kwong *et al.* (1988), the success in using leaf analysis to diagnose the nutrient status of potatoes, vines and tobacco in France prompted Pierre Halais and Norman Craig in Mauritius in 1936 to probe the feasibility of using foliar diagnosis in sugarcane. The encouraging results they obtained in observing that omission of either P or K from the fertiliser formulation was immediately reflected in the top visible dewlap leaf composition of sugarcane (Craig, 1938) paved the way for the application of foliar diagnosis in P as well as in N and K management of sugarcane. Craig (1938) further showed that cane yield response to P fertiliser was small when the leaf P level exceeded 0.35% P_2O_5 but became progressively larger when the leaf P value fell below 0.30% P_2O_5.

Though the positive correlation between leaf P and sugarcane response to P fertiliser decisively showed that foliar diagnosis could be an invaluable tool to uncover P deficiencies in sugarcane, estimates of the optimum or threshold leaf nutrient P level was missing for foliar diagnosis to be really useful. In that context using P leaf data of five varieties of ratoon canes grown in localities where the yield approached maximum and where liberal applications of NPK fertiliser had been practised, Craig (1940) established an optimum leaf P value of 0.38% P_2O_5 (i.e. 0.17% P) for sugarcane. This threshold leaf P value has over the years been refined and a value of 0.19% P is now adopted for sugarcane irrespective of variety and soil type in Mauritius.

The practice of foliar diagnosis has itself changed little since Craig and Halais (1944) drew up the leaf sampling rules which are still very much valid today. However with the regular use of NPK fertilisers and scums by the sugarcane planting community, the need to sample every sugarcane field is no longer necessary. Instead the nutritional P (as well as the N and K) status of the cultivated sugarcane in Mauritius is followed through the foliar diagnosis of leaves sampled in about 600 *permanent sampling units* (a permanent sampling unit is fully representative of a section of a sugar estate in terms of soil types and management practices).

Interpretation of the nutritional P status and trends of the sugarcane is done as outlined in Table 3.5 and is based on a three year running average of the leaf P values obtained on analysis to minimise the disturbing influence of climate.

Table 3.5: Interpretation of sugarcane leaf P values.

No. of years with leaf P value higher than 0.19%	P nutrient status
3	High
2	High (doubtful)
1	Low (doubtful)
0	Low

Once a permanent sampling unit has been diagnosed to have a low P nutrient status, a corrective P dressing is applied to the whole section of the estate it represents, which otherwise would not have received P in ratoon cane.

Foliar diagnosis has on a number of occasions played a key role in avoiding potential losses of sugar production. Thus in the late 1950s it showed that P deficiency in sugarcane was increasing in every region of Mauritius as a result of (i) clearing and planting of new lands, some of them marginal in fertility and extremely deficient in P; (ii) deep cultivation such as derocking and sub-soiling old lands with heavy equipment resulting in large amounts of subsoil which is extremely poor in P being brought to the surface. Their admixture with top soils resulted in a general deterioration of the P status of the field so treated; and (iii) the complete inadequacy of P fertiliser practices. Foliar diagnosis results led to the application of corrective dressings of guano/rock phosphate which eliminated the worsening and impending P deficiencies.

3.3.3.3 Data processing and presentation

In Mauritius, the sugarcane crop (*Saccharum hybrid sp.*) is grown by planting cut pieces of cane (cane setts) and this provides the plant cane 15 to 18 months later. After harvesting the plant cane by cutting at ground level during the period June to November, the regrowth gives rise to the first ratoon crop which is in turn similarly harvested 12 months later. The crop is ratooned repeatedly thereafter until the yield declines to such an extent

that replanting is worthwhile. In general, a field is only replanted every seven to eight years, that is, after a plant crop and six or seven ratoons.

Furthermore, studies in Mauritius on the residual value of rock phosphate showed that when sufficient amount of P had been applied to sugarcane at planting, supplementary P fertilisation in the ratoons was superfluous (Cavalot *et al.*, 1988). Accordingly it is current practice in Mauritius to apply P fertilisers in the furrows only at planting. In this study soil P test data were compiled for two different periods, namely 1997/1998 and 2005/2006. Soils receiving P at planting in 1997/1998 will only be P fertilised again if needed in 2005/2006. A comparison of soil P status in 1997/1998 with that of 2005/2006 will therefore provide an indication of how soil P under sugarcane is evolving with time over a sugarcane crop cycle under the current P management practices.

The soil P test data for small planters were obtained from the records which are already available at the Mauritius Sugar Industry Research Institute (MSIRI) since the latter institution offers a free soil testing service to this category of sugarcane planters. Results of soil analyses for large planters were obtained from the records of sugar estates who perform their own soil testing. Based on the table of interpretation of soil P test in Mauritius shown in Table 3.4, the soil P status has been categorised, for the purpose of this study into four P fertility classes which are shown in Table 3.6. It needs to be emphasized that all the soil P test values have been obtained using 0.1M H_2SO_4 as the extractant. The required calculations and graphical presentations of data were done using the Microsoft Excel 2003 program on Windows XP.

Table 3.6: Phosphorus fertility classes of soils under sugarcane in Mauritius using 0.1M H_2SO_4 as the extractant.

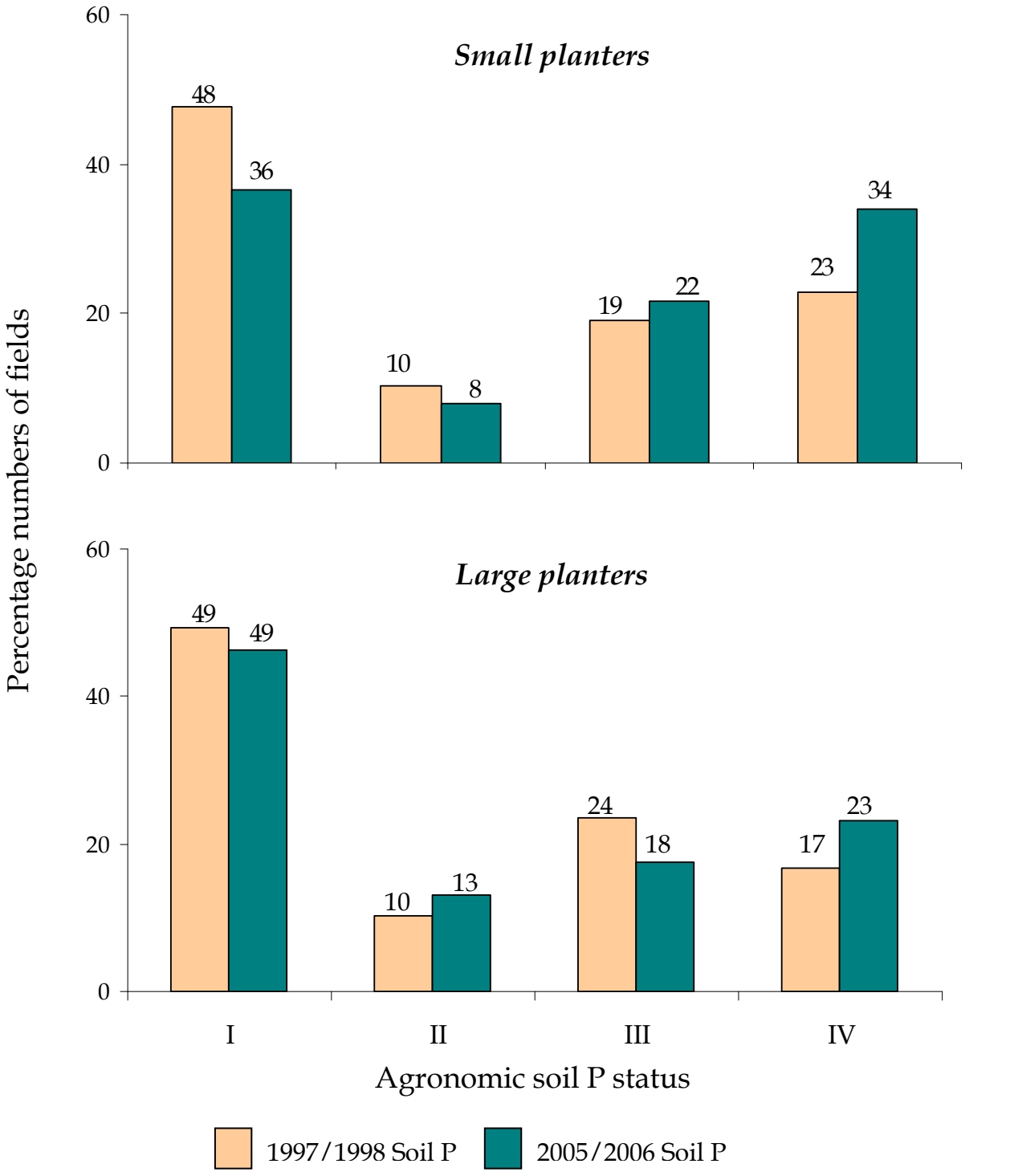
Fertility class	**Soil test P range** ***0.1M H_2SO_4-P (mg kg^{-1})***	**Fertility class description**
I	P < 80	Deficient to adequate
II	80 ≤ P < 100	Optimum
III	100 ≤ P < 150	Excessive to highly excessive
IV	P ≥ 150	Highly excessive

3.3.3.4 Evolution of P status of soils under sugarcane

In the absence of a reliable soil P test in the 1950s but with sufficient confidence having been gained that foliar diagnosis could be relied upon to disclose accurately the integrated influence of manuring on P nutrition of sugarcane, foliar diagnosis was used to examine the P status of the soils in Mauritius. The conclusion was drawn that 30% of the sugarcane lands at that time was deficient in P (Parish, 1964) and that the P status of the cane was determined primarily by the type of holdings (namely large or small planters) with climate and soil type playing only minor roles in Mauritius. While lands owned by large planters tended to be well supplied with P, a deficiency of P was invariably noticed in small planters' lands particularly those located in the super-humid regions. As mentioned in section 3.3.3.2, corrective P fertiliser recommendations were formulated with liberal applications of P being recommended to sugarcane, as a cheap source of P (guano/rock phosphates) was available from the outer islands belonging to Mauritius.

Thereafter up to the 1980s, P fertilisation of sugarcane in Mauritius was based on the maintenance concept which calls for the complete replacement of P exported by sugarcane without giving any due regard to the inherent capacity of the soil to provide some or all of the P needed by the crop. Phosphorus being immobile in the soil and not lost by leaching or volatilisation, as reviewed in section 2.4, the adoption of the maintenance concept in P fertilisation of sugarcane must have lead to a build-up of P in the soils of Mauritius and little P deficiency should be encountered.

Yet examination of the soil test P data of fields to be replanted with the sugarcane during the period 1997/1998 showed that 48% of the land occupied by small planters required P fertilisation. The picture is not different for the large planters with 49% of their land requiring P fertilisation indicating that any difference that may have existed in the P management of sugarcane lands by small and large planters in the 1950s must have disappeared over time. Also interesting to note was the fact that approximately 40% of the land of both the small and large planters already contained an excess of P ($P \geq 100$ mg kg^{-1}) in 1997/1998 and that soils with the optimum soil P (80 to 100 mg kg^{-1}) was not extensive for both planter categories (Figure 3.8).



I: Deficient to adequate; P< 80 mg kg^{-1}

II: Optimum ; 80 ≤ P < 100 mg kg^{-1}

III: Excessive to highly excessive; 100 ≤ P < 150 mg kg^{-1}

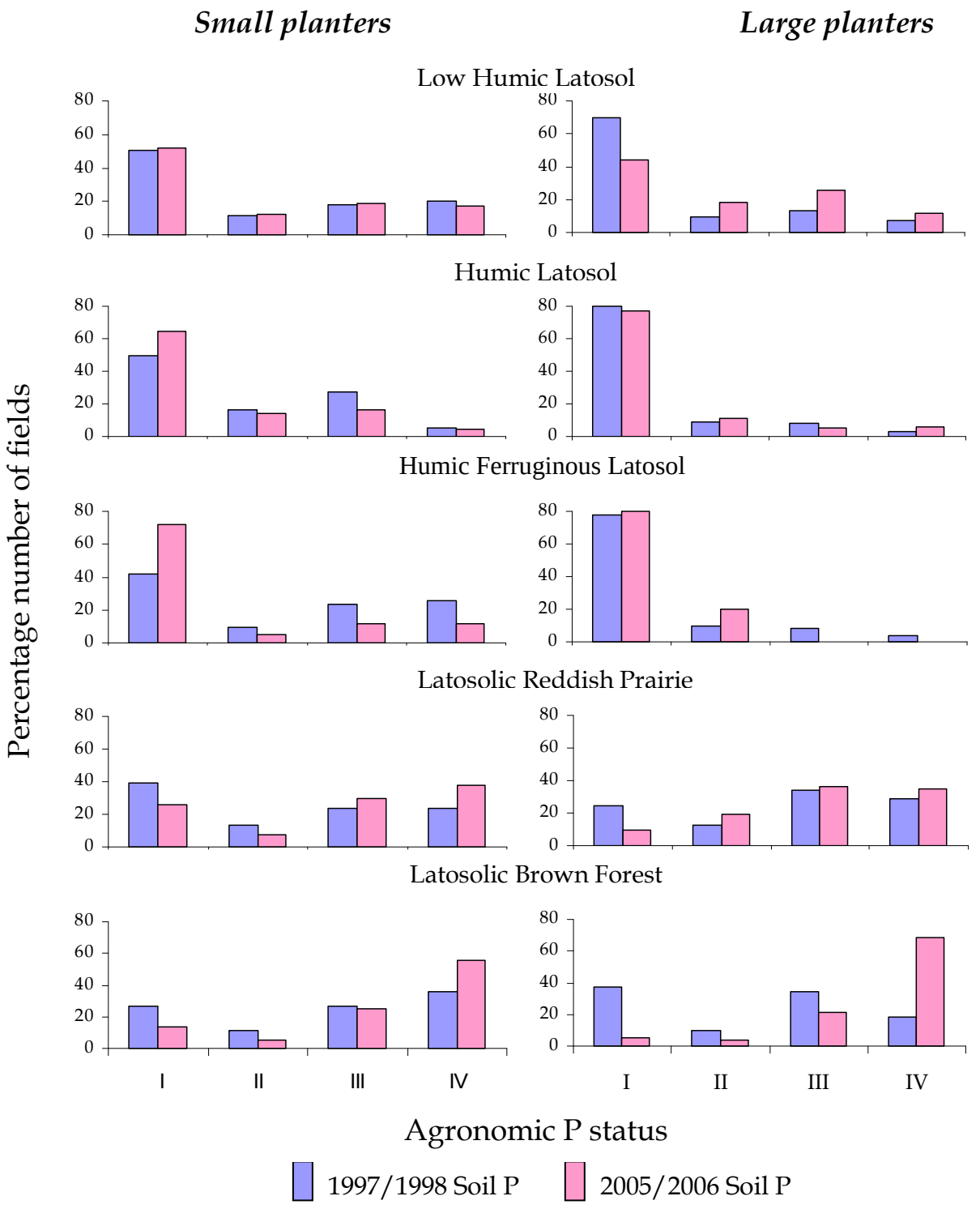
IV: Highly excessive; P ≥ 150 mg kg^{-1}

Figure 3.8: Evolution of soil P fertility status for fields managed by small and large sugarcane planters from the period 1997/1998 to 2005/2006.

In the late 1990s, P fertilisation philosophy based on the sufficiency concept, whereby P should be applied at rates determined by the soil test P, was introduced to take into account the capacity of the soil to provide at least part of the P requirements of the sugarcane crop. This change in P fertilisation philosophy did not seem to have any bearing on the extent of soils of both categories of planters having an excessive soil P status. On the contrary soils of small planters with a highly excessive soil P status (P ≥ 150 mg kg^{-1}) rose from 23% in 1997/1998 to 34% in 2005/2006 while for large planters' land the increase was from 17% to 23% over the same crop cycle, indicating a greater readiness among large planters to adopt the sufficiency concept. The data in Figure 3.8 therefore show that with the current P management practice in sugarcane, the P status of soils in Mauritius will shift more and more towards an excess of P in soils in spite of the recommendations to the planting community to adopt the sufficiency concept.

A survey of the P nutritional status of sugarcane in the early 1960s using the three year running average foliar data of the permanent sampling units had revealed that the poor P status was particularly prominent in the Low Humic Latosol soils and Latosolic Reddish Prairie soils of the west and north of the island (Halais, 1964). Analysis of the soil P test data in this study showed that a very different picture has emerged since the 1960s. For the large planters, the soils requiring P fertilisation in the late 1990s belonged to well-developed latosol groups (i.e. Low Humic Latosol, Humic Latosol and Humic Ferruginuous Latosol). Few fields of these soil groups contained highly excessive soil P. The same observation may be made for small planters though the percentage of their fields in those three soil types with an excessive soil P status was higher than for large planters.

The rocky and less well-developed latosolic soils (Latosolic Reddish Prairie and Latosolic Brown Forest) were on the other hand endowed with a substantial portion of sugarcane fields containing excessive P levels. For these poorly developed soils P fertilisation, as shown by the soil test P data collected for the period 2005/2006, has served for both planter categories to exacerbate from an agronomic point of view the extent of their sugarcane fields with an excessive P levels (Figure 3.9).



I: Deficient to adequate; P< 80 mg kg^{-1}

II: Optimum ; 80 ≤ P < 100 mg kg^{-1}

III: Excessive to highly excessive; 100 ≤ P < 150 mg kg^{-1}

IV: Highly excessive; P ≥ 150 mg kg^{-1}

Figure 3.9: The agronomic P status of sugarcane fields on the five main soil groups in Mauritius belonging to the large and small planters.

3.4 Conclusions

A review of the history of P fertiliser usage by the sugar industry in Mauritius has been very informative in showing that the planting community was fully conscious even at the beginning of the 20th century of the need of adequate P (as well as N and K) nutrition of the sugarcane for the industry to be profitable and sustainable. The policy of intensive P (and NK) fertilisation adopted since the late 1940s and early 1950s, have lead to approximately 32,000 hectares (53%) of sugarcane lands in Mauritius to contain more P (i.e. P ≥ 100 mg kg^{-1}) than what is actually needed by the sugarcane crop (Figure 3.10).

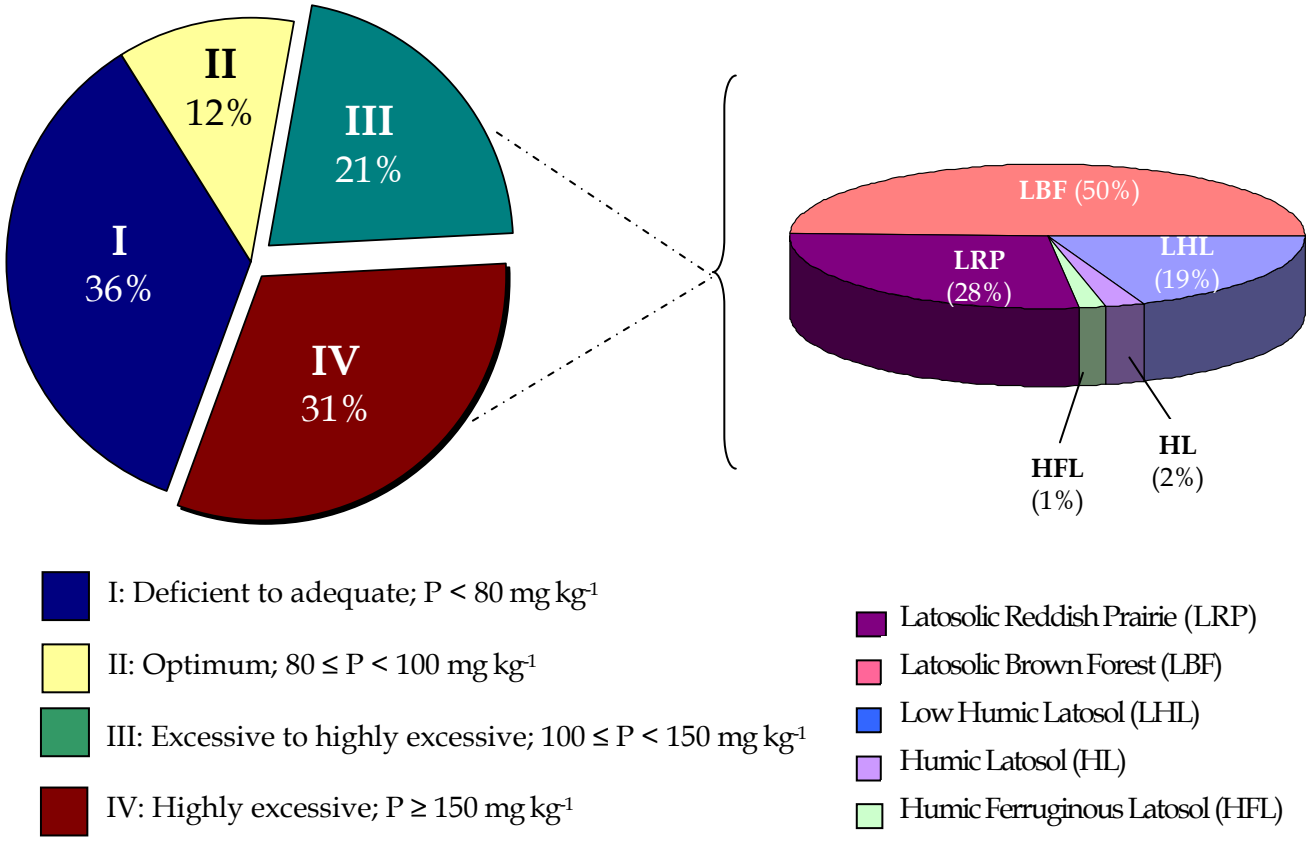


Figure 3.10: 2005/2006 phosphorus status of soils in Mauritius and the distribution of the fields with an excess of P for sugarcane growth among the five main soil types.

More importantly the data obtained show that with the foreseeable continuing intensive use of P fertilisers and in spite of shifting the philosophy of P fertiliser application from one of maintenance to that based on sufficiency, the area of land with too much P for

sugarcane growth will go on rising in the future if no remedial measures are taken. Moreover it is also clear from the data obtained on soil P status in 2005/2006 that there is no difference in P management between small and large planters and that fields with an excess of P belong to all soil groups (Figure 3.10) and are present throughout the island, though they have a tendency to be concentrated in the Latosolic Brown Forest soils of the high rainfall areas. How much of these soils with an excess of P for sugarcane growth actually represent a hazard to freshwater sources in Mauritius remains unknown since no soil P test is to-date available for their identification, hence the need for undertaking the present study.

4 Elaboration of an environmental soil P test and establishment of a threshold P level in soils to protect Mauritian freshwater sources

4.1 Introduction

The importance of P in sugarcane production, as reviewed in Chapter 3, has been recognised for more than a century in Mauritius. Accordingly considerable research has been carried out on the P needs of sugarcane and on the effect which intensive P management, as practised over the past 50 years, is having on the soil P status. A reliable soil P test has been developed to accurately describe the soil P status from the sugarcane nutritional viewpoint.

However in spite of the extensive information now available on soil P status, its significance from the freshwater protection angle remains unknown due mainly to a lack of a suitable environmental soil P test method. To close this gap in knowledge, a research effort to develop such a soil P test as well as to establish an environmental threshold for P in the main soils of Mauritius cannot be more timely. From this perspective, evidence presented in the literature (e.g. McDowell and Sharpley, 2001a) showed that a laboratory based extraction of soil with 0.01M $CaCl_2$ gives a very reliable representation of the P that will be observed in runoff. Accordingly instead of having an experimental set up in the field to collect runoff from simulated rainfall, the P extractable in a 0.01M $CaCl_2$ solution was determined in soils of Mauritius to provide an accurate indication of the concentration of P that would be found in runoff waters.

An environmental soil test P, as pointed out by McDowell and Sharpley (2001b), must take into account all specific soil P reactions, otherwise the results obtained will be limited to the particular soil studied. To satisfy these criteria, the concept of degree of P saturation (DPS_{ox}) has been developed to integrate the dominant soil characteristics controlling soil P sorption-desorption reactions (Beck *et al.*, 2004). In so doing, the DPS becomes independent of the variations in soil properties and when determined by a single extraction with acid ammonium oxalate (DPS_{ox}) it had been found to be a very reliable pointer of P susceptibility to loss from agricultural soils (Beck *et al.*, 2004). Ammonium

oxalate extractable P, Al and Fe in mmol kg^{-1} was therefore determined in soils and percentage degree of P saturation (DPS_{ox}) computed using the formula:

$$DPS_{ox} = \frac{100\ P_{ox}}{Fe_{ox} + Al_{ox}}$$

Once the 0.01M $CaCl_2$-P concentrations and their corresponding DPS_{ox} values have been measured, the relationship between 0.01M $CaCl_2$-P concentration and DPS_{ox} can be established by the split line model as described by McDowell and Sharpley (2001a). The split line model indicates a change point (a DPS_{ox} threshold) above which the P is not retained (or with difficulty) by the soil and is thus available for transport.

The ammonium oxalate extraction to determine DPS_{ox} in soils however is tedious and time consuming and consequently it is very unlikely to be used in routine soil testing. Extraction of P from the soil with 0.1M H_2SO_4 is on the other hand, easy to perform and it is already a common procedure in agronomic soil P testing in Mauritius. To be able to use 0.1M H_2SO_4 extraction in environmental soil P testing, the relationship between DPS_{ox} and 0.1M H_2SO_4-P has to be established. This has been carried out by conventional statistical regression techniques. The value of 0.1M H_2SO_4-P in soils that corresponds to the threshold DPS_{ox} arrived at, as explained above, by the split line model will be the environmental soil P threshold.

Apart from giving a description of the measurement of the soil characteristics pertinent to this study, namely pH, cation exchange capacity, soil texture, organic matter content and exchangeable bases, this chapter will therefore also describe and report the values of 0.1M H_2SO_4-P, 0.01M $CaCl_2$-P and DPS_{ox} for the main soil groups under sugarcane in Mauritius. This chapter will moreover discuss how the different forms of P are influenced by the soil properties determined. A third component included in the chapter is the relationship that exists among the three different forms of P and the derivation of a value of 0.1M H_2SO_4-P that would represent the threshold above which P in soil will be mobilised to potentially contaminate the freshwater sources in Mauritius.

4.2 Materials and methods

4.2.1 Selection of soil samples

In all 112 soil samples representing the main soil groups under sugarcane cultivation in Mauritius namely: (i) Low Humic Latosol, (ii) Latosolic Reddish Prairie, (iii) Humic Latosol, (iv) Humic Feruginous Latosol and (v) Latosolic Brown Forest were chosen for the present study. The soil samples originated from previous research projects of the Mauritius Sugar Industry Research Institute. They were selected as shown in Table 4.1 to cover a range of 10 to 250 mg kg^{-1} P extractable by 0.1M H_2SO_4 which, as explained in section 4.1, is used for agronomic soil P testing in Mauritius.

After sampling as described in STASM (2003), the soils were air-dried, then passed through a 2mm sieve and kept in labelled plastic containers for analysis.

Table 4.1: Range of 0.1M H_2SO_4 extractable P in the soils used in the present study.

Soil group [Number of samples]	Range of 0.1M H_2SO_4 extractable P (mg kg^{-1})
Low Humic Latosol [27] *Humic Nitosol**	13 to 210
Humic Latosol [18] *Humic Nitosol*	19 to 196
Humic Ferruginous Latosol [21] *Humic Acrisol*	13 to 140
Latosolic Reddish Prairie [18] *Eutric Cambisol*	35 to 220
Latosolic Brown Forest [28] *Dystric Cambisol*	22 to 244

* Soil group as per FAO classification (Arlidge and Wong You Cheong, 1975)

4.2.2 Soil P tests

In each of the 112 selected soil samples, the P extractable in 0.1M H_2SO_4, in 0.01M calcium chloride ($CaCl_2$) and in 0.2M ammonium oxalate (NH_4Ox) were determined as described in the sections below.

4.2.2.1 Agronomic soil P test

The P extractable in 0.1M H_2SO_4 was determined by the method described by Cavalot *et al.* (1988). It involved shaking 1g air-dried soil (< 2mm) with 50ml of 0.1M H_2SO_4 for one hour. The suspension was centrifuged at 2000 rpm for 10 minutes before filtering through a Whatman No. 41 filter paper. The P concentration in the solution was determined by the method of Murphy and Riley (1962).

4.2.2.2 Calcium chloride extractable-P

The calcium chloride extractable-P ($CaCl_2$-P) was determined by shaking 10g of air-dried soil (< 2mm) in 50ml of 0.01M $CaCl_2$ solution for 30 minutes as outlined by Beck *et al.* (2004). After centrifuging for 10 minutes at 2000rpm and filtering through a Whatman No. 42 filter paper, the P concentration in the extract was determined by the method of Murphy and Riley (1962).

4.2.2.3 Degree of P saturation

The degree of P saturation (DPS_{ox}) in the soils was determined by ammonium oxalate extraction as outlined by Beck *et al*. (2004). It involved shaking 0.25g of finely ground soil (< 0.25mm) for two hours in the dark with 50ml of 0.2M ammonium oxalate solution, containing 2.5mg L^{-1} polyacrylamide and adjusted to pH 3. The suspension was then centrifuged at 2000rpm for 10 minutes and filtered through a Whatman No. 40 filter paper.

The concentration of P in the extract was determined by digesting a 10ml aliquot with 5ml of concentrated nitric acid at 100°C in order to eliminate interference of the oxalate reagent during P determination (Szilas *et al.*, 1997). After digestion to dryness, the residue was dissolved in 2ml 0.3M H_2SO_4 and brought to a volume of 50ml with distilled water. The P concentration in the resulting solution was measured by the method of Murphy and Riley (1962).

While the concentrations of iron in the ammonium oxalate extracts (Fe_{ox}) were determined by atomic absorption spectrophotometry (Varian, AA10BQ), those of aluminium (Al_{ox})

were measured on a graphite furnace atomic absorption spectrophotometer (Perkin Elmer, AA700).

The ammonium oxalate degree of P saturation (DPS_{ox}) expressed as a percentage was computed with the formula given earlier in section 4.1.

4.2.3 Characterisation of the selected soil samples

The 112 selected soil samples were characterised for pH (H_2O), particle-size distribution, organic carbon and exchangeable calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na). The cation exchange capacity (CEC) was taken to be the sum of the concentration of the four exchangeable bases. The analytical methods employed are described in the following sections.

4.2.3.1 pH (H_2O)

The pH was determined electrochemically in the laboratory using a pH meter (Denver Instrument, model 15). In effect the potential of the hydrogen ion electrode in a suspension of 20g soil in 50ml distilled water was read against that of a calomel reference electrode as described by STASM (2003). The pH meter was first calibrated using buffer solutions of pH 4 and 7.

4.2.3.2 Particle-size distribution

For particle size analysis, the soil aggregates were first dispersed by chemical and mechanical means as indicated by Gee and Bauder (1986) before separating the individual particles according to size limits by sieving (sand fraction) and sedimentation (silt and clay fractions). The sedimentation relies on the relationship between settling velocity and particle diameter (Stoke's 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 destroy it by heating 10g of air-dried soil (< 2mm) with 2g sodium metabisulphite and 50ml 10% H_2O_2 until the contents of the beaker was reduced to half its original volume. The oxidation process using H_2O_2 was repeated twice to ensure that all

organic matter had been destroyed. Once the oxidation process was complete, the soil was dispersed by shaking with sodium hexametaphosphate for 16 hours and maintained in the dispersed state until sedimentation was completed.

The silt content was determined in a constant temperature room at 20°C by pipetting a 20ml sample at a depth of 10 cm from the suspension after the critical time required (approximately 4.5 minutes after shaking by repeated inversions for 30 seconds) for the silt fraction to settle. The clay content was similarly determined through pipetting at the critical time (after 7 hours). The remaining silt and clay were siphoned off leaving the sand material which was collected and dried.

4.2.3.3 Organic matter

The organic carbon content of the soils was determined in the laboratory by the modified Walkley-Black procedure as described by Anderson and Ingram (1989). In this procedure, soil organic carbon was partially oxidized by treating 0.5g of finely ground (< 0.25mm) air-dried soil with 10ml of 5% potassium dichromate solution acidified with 20ml concentrated sulphuric acid for at least 2 hours. After completion of this oxidation reaction, 50ml of barium chloride solution was added and the mixture was centrifuged at 2500rpm for 10 minutes. The concentration of chromium ions in the reduced state in the supernatant obtained was measured colorimetrically at 600nm using a spectrophotometer (Analytik Jena, Specord 40). Since this concentration is directly proportional to the amount of organic carbon in the sample, the latter was deduced from chromium ion concentration and converted to organic matter by multiplying by the commonly adopted factor of 1.724.

4.2.3.4 Exchangeable bases and CEC

The concentration of the exchangeable bases was determined in the laboratory by leaching the soil with unbuffered ammonium acetate as described by Peech (1945) for the determination of cation exchange capacity. Initially, 5g of air-dried soil (< 2mm) was leached with 1M unbuffered ammonium acetate solution to displace the exchangeable Ca, Mg, K, and Na. The concentrations of the Ca and Mg in the leacheate were determined by atomic absorption spectrophotometry (Varian, AA10BQ) while the concentration of K and

Na was read on a flame photometer (Gallenkamp flame analyser). The CEC of the soil was calculated by the summation of the exchangeable cations Ca, Mg, K and Na obtained.

4.2.4 Data processing and interpretation

The experimental data were processed using Microsoft Excel 2003 program in Windows XP. This program was used for both calculations of mean and standard deviation and for graphical presentations of the data. The standard error was calculated using the equation below:

$$\text{Standard error} = \frac{\text{Standard deviation}}{\sqrt{(\text{No. of samples})}}$$

The split line models were constructed from the 0.01M $CaCl_2$-P data (y-axis) and their corresponding DPS_{ox} values using the *R^2 lines procedure* option available from the GenStat (11^{th} edition) software which generates two lines with different slopes meeting at a point of interception (also referred to as the change point).

The regression models were constructed using the CurveExpert 1.3 program in Windows XP. The built-in curve finder tool in the program which sifts through every possible curve fit was used to choose the most suitable model based on their r^2 value and standard errors. The correlations between the soil properties and the soil P tests were done with the dependent variable (y-axis) being the soil P tests and the individual soil properties as the independent variable (x-axis). The correlation which exists between the 0.1M H_2SO_4-P and the DPS_{ox} was also established, with the DPS_{ox} on the x-axis and the 0.1M H_2SO_4-P on the y-axis.

Moreover multiple linear regression analyses were carried out on the experimental data obtained for the soil properties and the soil P tests using the *multiple regression* function in the SPSS statistical package (standard version) in Windows XP. The individual soil P test was set as the dependent variable while the different soil properties were considered as the independent variables.

4.3 Results and discussion

4.3.1 Characteristics of the main soils under sugarcane in Mauritius

The characteristics determined in the five main soils under sugarcane in Mauritius are summarised in Table 4.2 and are listed in Appendix 1. On the whole, the soils in Mauritius are slightly acidic to near neutral with a mean pH range of between 5.2 and 6.0. Soil pH values higher than 7.5 were recorded on only one occasion in a Low Humic Latosol. As stated by Pierzynski *et al.* (2005), the speciation of P in soil solution is primarily a function of pH and in soils with pH values in the range of 4.1 to 7.3, P fixation would be dominated mostly by the presence of hydrous oxides of iron and aluminium and to a lesser extent by calcium carbonates. An increase in soil pH would decrease the activity of Fe and Al thereby resulting in a lower P adsorption/precipitation and a higher P concentration in solution (Havlin *et al.*, 2005a).

In general, the texture of the main soils in Mauritius ranges from clayey to clay loam with an average of not less than 33.7% clay (Table 4.2). The clay content in the Low Humic Latosol may on average even be as high as 68.8%. In fact the clay content decreased from the Low Humic Latosol to the Humic Latosol and to the Humic Ferruginous Latosol for the Latosol group and from Latosolic Reddish Prairie to the Latosolic Brown Forest soils for the Latosolic group indicating that the clay content tends to diminish with increasing rainfall (see section 3.3.1). As soils with higher clay contents are generally known to fix more P than soils with low quantities of clay (Havlin *et al.*, 2005a), it is expected that soils such as the Low Humic Latosol located in the low rainfall zone will be fixing more P than the soils in the wet regions of Mauritius such as the Humic Ferruginous Latosol. For such soils in the low rainfall zone, it might therefore be necessary to add larger quantities of P fertilisers in order to maintain an optimum level of soil solution P for sugarcane growth.

Differences in the CEC and concentration of the exchangeable bases among the main soil groups in Mauritius are related to rainfall which affects the intensity of leaching in the soils (Cavalot *et al.*, 1988). The mean CEC among the main soils ranged from 4.93 to 14.01 $cmol^{+}\ kg^{-1}$, with the lowest CEC being encountered in the soils formed in the high rainfall

Table 4.2: Pertinent soil properties (mean ±SE) of the five main soil groups under sugarcane in Mauritius.

Soil group	pH (H_2O)	Organic matter	Particle-size analysis			Exchangeable bases				Cation exchange capacity
			Clay	Silt	Sand	K	Na	Ca	Mg	
		%	%			$cmol^+ kg^{-1}$				
Low Humic Latosol (*Humic Nitosol*) *	5.6 ±0.2	4.2 ±0.2	68.7 ±2.7	17.3 ±1.1	14.0 ±1.7	0.51 ±0.06	0.34 ±0.04	5.92 ±0.77	3.21 ±0.45	10.0 ±1.2
Humic Latosol (*Humic Nitosol*) *	5.2 ±0.2	4.7 ±0.2	54.0 ±4.2	23.8 ±1.8	22.2 ±2.7	0.37 ±0.04	0.24 ±0.03	5.19 ±1.51	1.61 ±0.32	7.4 ±1.7
Humic Ferruginous Latosol (*Humic Acrisol*) *	5.5 ± 0.2	5.3 ±0.2	33.7 ±2.5	32.6 ±1.5	33.7 ±1.6	0.24 ±0.04	0.22 ±0.02	4.16 ±1.09	1.26 ±0.26	5.9 ±1.3
Latosolic Reddish Prairie (*Eutric Cambisol*) *	6.0 ±0.2	5.4 ±0.6	47.6 ±2.9	25.4 ±1.3	27.0 ±2.6	1.06 ±0.22	0.47 ±0.05	8.44 ±1.18	4.04 ±0.51	14.0 ±1.7
Latosolic Brown Forest (*Dystric Cambisol*) *	5.3 ±0.1	7.0 ±0.5	39.6 ±2.2	30.4 ±1.4	30.0 ±1.6	0.45 ±0.04	0.30 ±0.02	2.49 ±0.21	1.70 ±0.16	4.9 ±0.3

*Soil group as per FAO classification (Arlidge and Wong You Cheong, 1975).

regions, namely the Humic Ferruginous Latosol and the Latosolic Brown Forest (Table 4.2). Correspondingly, low concentrations of exchangeable bases (K, Na, Ca, Mg) were encountered in those soils. The results obtained show, in addition, that exchangeable Ca^{2+} is the predominant exchangeable base present in the main soils of Mauritius indicating that an appreciable amount of P would be present as precipitated Ca-P. Moreover as the presence of divalent cations on CEC enhances P adsorption (Havlin *et al.*, 2005a), the P adsorbed would tend to be lowest in soils with the least amount of exchangeable Ca^{2+}, namely in the Humic Ferruginous Latosol and Latosolic Brown Forest soils of the high rainfall zones.

4.3.2 Influence of soil properties on 0.1M H_2SO_4 extractable P

From Table 4.3, it is apparent that even after fitting the best fit single variable regression model, the correlation between the 0.1M H_2SO_4-P and each of the soil characteristics studied was low. Even when the latosols and latosolic soils were treated separately, the r^2 values did not rise above 0.28. Hence no single soil characteristic can be said to have a distinct influence on the amount of P extracted by the 0.1M H_2SO_4. It is more likely that the amount of 0.1M H_2SO_4-P is a function of the combined effects of all soil characteristics.

Multiple linear regression analysis indeed showed that the r^2 value can be raised to 0.30 by combining the influence of exchangeable Ca and organic matter in the soil. The correlation between the 0.1M H_2SO_4-P (mg kg^{-1}) and exchangeable Ca ($cmol^+$ kg^{-1}) and organic matter (%) may then be described by the following equation:

$$0.1M\ H_2SO_4\text{-}P = 4.156 + 5.281\ \text{exchangeable Ca} + 11.905\ \text{organic matter};\qquad r^2 = 0.30$$

The correlation is not improved by the inclusion in the regression of the other soil properties such as clay, indicating the little role that the clay plays in determining the 0.1M H_2SO_4-P level in soils.

However from the data obtained from the single variable regression equations certain trends could be discerned. Thus as soil pH value increases, the 0.1M H_2SO_4-P also shows a tendency to rise (Figure 4.1). This tendency of the 0.1M H_2SO_4-P to increase with pH may

Table 4.3: Correlation between 0.1M H_2SO_4 extractable P (y) and pH, organic matter, clay, exchangeable Ca and cation exchange capacity (x) in the main soils under sugarcane in Mauritius.

Soil property (x)	Data set	Regression model and coefficient data	r^2 value
pH (H_2O)	All soils	$y=1/(ax+b)$ a= -0.002, b= 0.024	0.13
	Latosols	$y=a+bx+cx^2$ a= 389, b= -135, c= 14	0.20
	Latosolic soils	$y=ax^{(bx)}$ a= 55, b= 0.1	0.07
Organic matter (%)	All soils	$y=ax^{(bx)}$ a= 70, b= 0.03	0.15
	Latosols	$y=a+bx+(c/x^2)$ a= 188, b= -11, c= -973	0.06
	Latosolic soils	$y=ax^{(bx)}$ a= 79, b= 0.02	0.22
Clay (%)	All soils	$y=a+bx+(c/x^2)$ a= 210, b= -2, c= -53925	0.09
	Latosols	$y=a(b^x)(x^c)$ a= 0.004, b= 0.932, c= 3.490	0.13
	Latosolic soils	$y=ab^x$ a= 190, b= 1.0	0.08
Exchangeable Ca ($cmol^+ kg^{-1}$)	All soils	$y = ae^{[-(x-b)^2]/2c^2}$ a= 155, b= 20.2, c= 15.4	0.15
	Latosols	$y = ae^{[-(x-b)^2]/2c^2}$ a= 160, b= 19, c= 12	0.28
	Latosolic soils	$y=ax^{(bx)}$ a= 101, b= 0.01	0.07
Cation exchange capacity ($cmol^+ kg^{-1}$)	All soils	$y=a+bx$ a= 71.2, b= 2.9	0.11
	Latosols	$y=a+bx$ a= 57, b= 3.41	0.16
	Latosolic soils	$y=ax^{(bx)}$ a= 99, b= 0.005	0.05

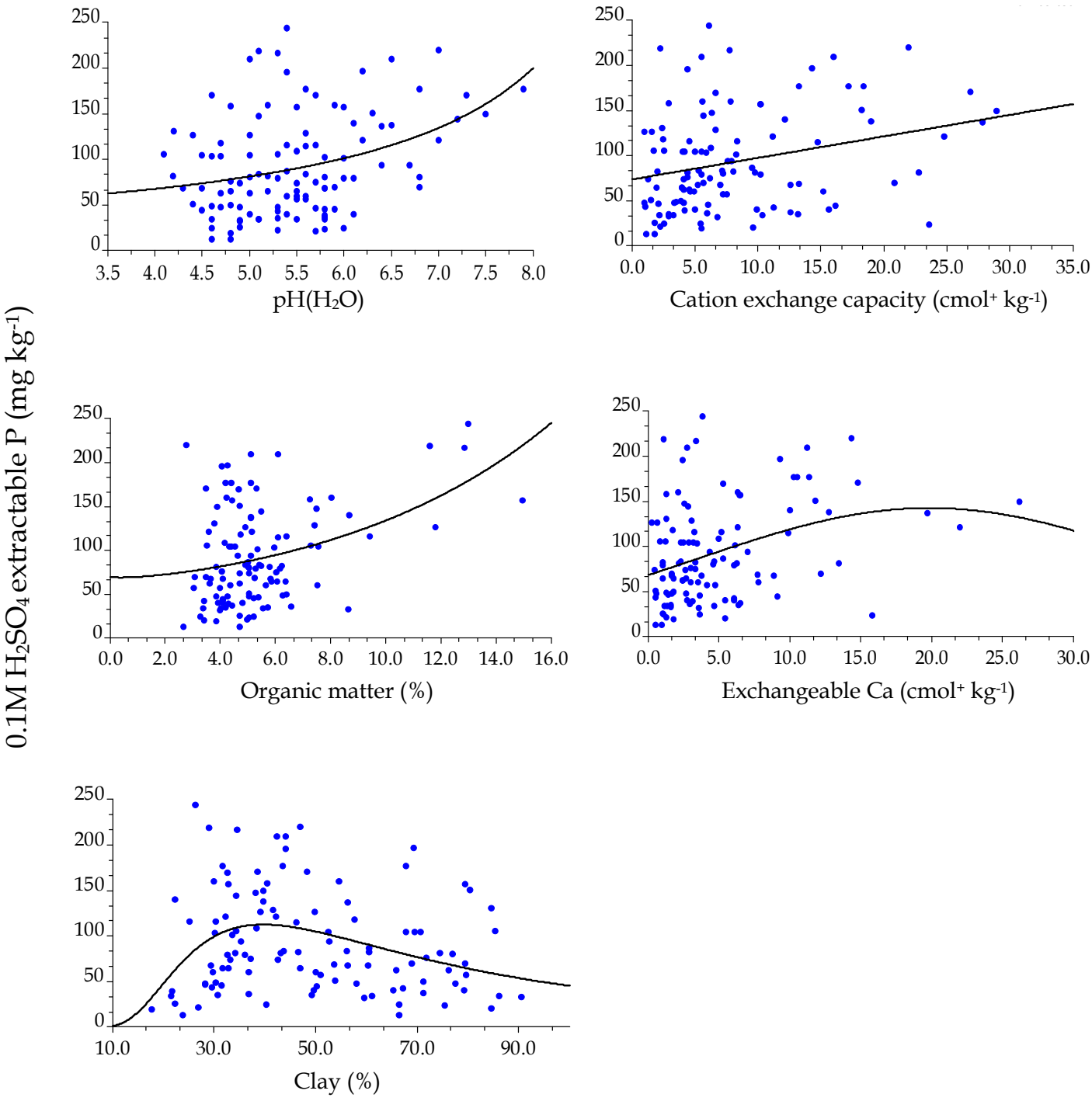


Figure 4.1: 0.1M H_2SO_4 extractable P as a function of pH (H_2O), organic matter (%), clay (%), cation exchange capacity ($cmol^+ kg^{-1}$) and exchangeable calcium ($cmol^+ kg^{-1}$) in the main soils of Mauritius (data for all the soils have been grouped together).

be explained at least to some extent by the fact that, as indicated in section 4.3.1, an increase in soil pH would decrease the activity of Fe and Al. This would result in a lower P adsorption/precipitation and consequently in more P to being extracted by the acid. As the correlation between soil pH and 0.1M H_2SO_4-P is poor (r^2=0.13), the effect of soil pH is probably masked by some other intervening parameter in the system. The poor correlation that exists between soil pH and 0.1M H_2SO_4-P is a reason why soil pH has never been used as an index of soil P availability to sugarcane in Mauritius.

Likewise from Figure 4.1, it can be observed that as the clay content increases, the P extracted also rises before starting to decline gently. No attempt should be made to explain that relationship which has a r^2 value of only 0.09. As is the case with soil pH, the effect of the clay would at some stage become masked by the more dominant effect of another intervening soil parameter.

The poor correlation (r^2=0.15) found between 0.1M H_2SO_4-P and soil organic matter did not concur with the observation of Horst *et al.* (2001) who reported that application of organic matter to soils would enhance P availability by shifting the equilibrium among soil P fractions towards plant-available P. This divergence from the inference of Horst *et al.* (2001) may be due to the fact that the dilute acid extractant (0.1M H_2SO_4) solubilises mainly the inorganic P pool (in the form of Fe-P, Al-P and Ca-P) with little organic P being extracted (Anon, 1986).

In conclusion, the present study shows that none of the soil characteristics studied can be relied upon to provide an accurate pointer of the P that can be extracted by 0.1M H_2SO_4, that is, the P that will be available to sugarcane in the soils of Mauritius. Instead the determination of the soil characteristics shows that the 0.1M H_2SO_4-P in the soils of Mauritius tends to be independent of their properties.

4.3.3 Influence of soil characteristics on 0.01M $CaCl_2$ extractable P

The most suitable models to describe the relationship between the P concentrations in 0.01M $CaCl_2$ (henceforth referred to as 0.01M $CaCl_2$-P) and each of the soil characteristics

studied were also sought. In some instances, the best regression model fitted showed that a better correlation existed between the soil characteristics and the 0.01M $CaCl_2$-P than with the 0.1M H_2SO_4-P. Thus the r^2 value between CEC and 0.01M $CaCl_2$-P for all soils grouped together was 0.45 (Table 4.4, Figure 4.2) as opposed to only 0.11 with 0.1M H_2SO_4-P. In other instances, for example with organic matter, the correlation (r^2=0.01) with 0.01M $CaCl_2$-P was however poorer than with 0.1M H_2SO_4-P (r^2=0.15). In general the same inference as with 0.1M H_2SO_4-P can be drawn namely, the r^2 value between each of the soil parameters studied and the 0.01M $CaCl_2$-P was low indicating that in spite of a tendency for 0.01M $CaCl_2$-P to increase with rising pH, CEC, and exchangeable Ca (Figure 4.2), none of the soil characteristics can be used to predict satisfactorily the 0.01M $CaCl_2$-P that would be encountered in soil.

The low r^2 values observed between each of the soil characteristics and the 0.01M $CaCl_2$-P indicate that just as in the case of 0.1M H_2SO_4-P, the concentration of 0.01M $CaCl_2$-P, that is P that would be dissolved in runoff, would be the result of the combined effects of the soil characteristics determined and perhaps of some of the properties not determined in this study.

Multiple linear regression analysis has shown that the r^2 value can indeed be raised to 0.49 by adding the effects of CEC, clay and organic matter to explain the variation in the 0.01M $CaCl_2$-P. The correlation of the 0.01M $CaCl_2$-P (mg L^{-1}) with CEC ($cmol^+ kg^{-1}$), clay (%) and organic matter (%) together can be described by the following equation:

0.01M $CaCl_2$-P = 0.001867+ 0.00121 CEC + 0.000148 clay +0.000625 organic matter; r^2= 0.49

The inclusion of either exchangeable Ca or pH in the multiple linear regression model will not be appropriate since these two soil characteristics are themselves highly correlated to CEC.

Table 4.4: Correlation between 0.01M $CaCl_2$ extractable P (y) and pH, organic matter, clay, exchangeable Ca and cation exchange capacity (x) in the main soils under sugarcane in Mauritius.

Soil property (x)	Data set	Regression model and coefficient data	r^2 value
pH (H_2O)	All soils	$y = a - be^{-cx^d}$ a= 0.08, b= 0.07, c= 0.007, d= 3.33	0.23
	Latosols	$y = a - be^{-cx^d}$ a= 0.06, b= 0.05, c= 0.002, d= 4.26	0.25
	Latosolic soils	$y = a - be^{-cx^d}$ a= 0.09, b= 0.08, c= 0.002, d= 3.90	0.21
Organic matter (%)	All soils	$y=a+bx+cx^2+dx^3$ a= 0.026, b= -0.0002, c= -1.5e10^{-4}, d= 9.43e10^{-6}	0.01
	Latosols	$y=e^{a+(b/x)+ clnx}$ a= -0.68, b= -3.94, c= -1.71	0.01
	Latosolic soils	$y = a - be^{-cx^d}$ a= 0.073, b= 0.052, c= 3.145, d= -3.394	0.14
Clay (%)	All soils	$y=a/(1+be^{-cx})$ a= 0.026, b= 100, c= 0.181	0.14
	Latosols	$y=a/(1+be^{-cx})$ a= 0.025, b= 55, c= 0.146	0.19
	Latosolic soils	$y=a+bx+cx^2+dx^3$ a= -0.067, b= 0.005, c= -9.53e10^{-5}, d= 5.59e10^{-7}	0.10
Exchangeable Ca ($cmol^+ kg^{-1}$)	All soils	$y=a+bx$ a= 0.013, b= 0.002	0.42
	Latosols	$y=a+bx$ a= 0.013, b= 0.002	0.44
	Latosolic soils	$y=a+bx$ a= 0.018, b= 0.001	0.29
Cation exchange capacity ($cmol^+ kg^{-1}$)	All soils	$y=a+bx+(c/x^2)$ a= 0.013, b= 0.001, c= -0.006	0.45
	Latosols	$y=a+bx$ a= 0.010, b= 0.001	0.52
	Latosolic soils	$y=1/(a+bx^c)$ a= 56, b= -2.54, c= 0.79	0.36

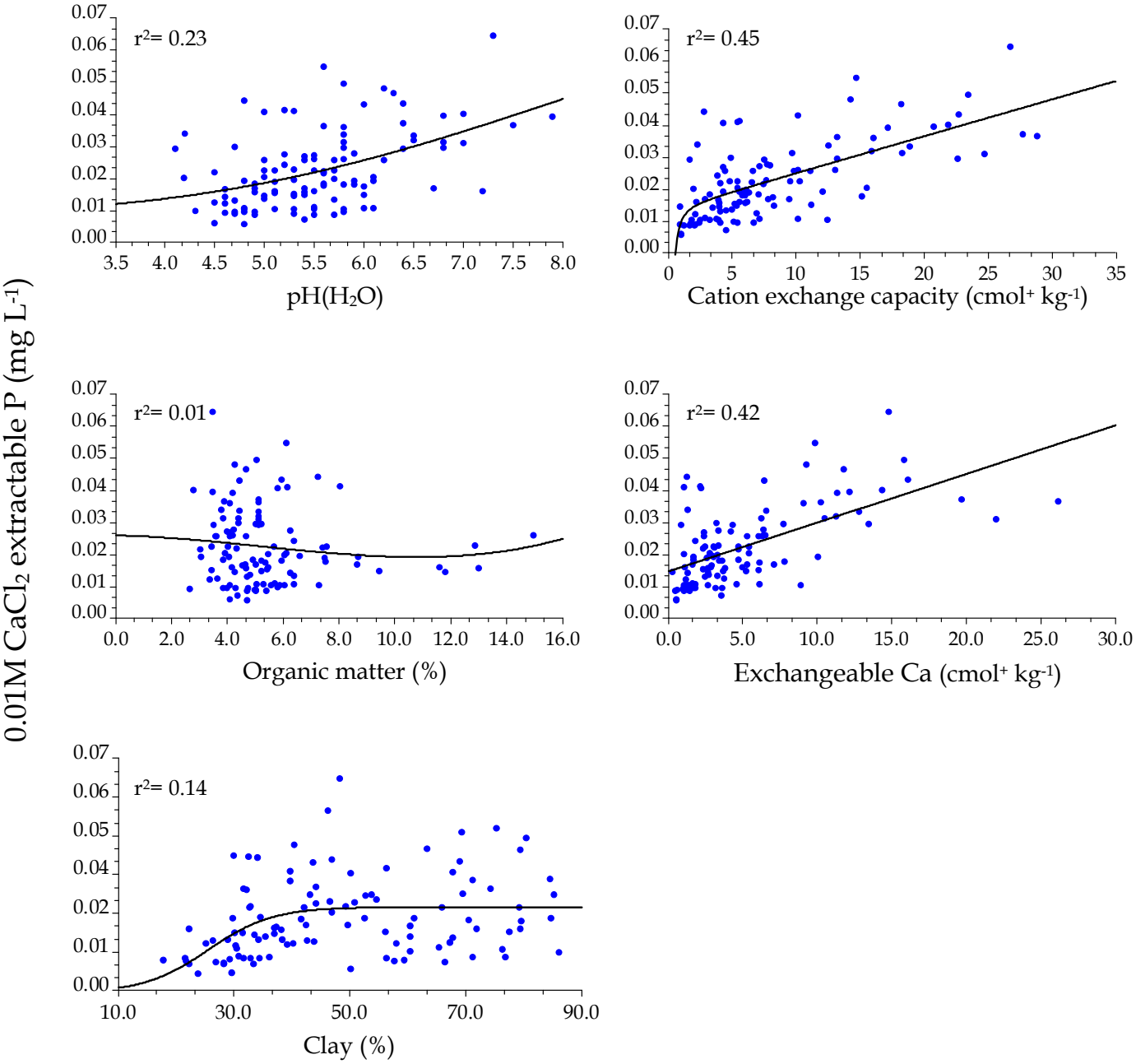


Figure 4.2: 0.01M $CaCl_2$ extractable P as a function of pH (H_2O), organic matter (%), clay (%), cation exchange capacity ($cmol^+ kg^{-1}$) and exchangeable calcium ($cmol^+ kg^{-1}$) of the main soils in Mauritius (data for all the soils grouped together).

4.3.4 Influence of soil characteristics on the degree of P saturation (DPS_{ox})

Just as for 0.1M H_2SO_4-P and 0.01M $CaCl_2$-P, the most appropriate models were sought to describe the relationship between DPS_{ox} and each of the soil characteristics determined. In general, similar to 0.1M H_2SO_4-P and 0.1M $CaCl_2$-P, the best regression models showed that the relationships between the soil properties and the DPS_{ox} were poor (Figure 4.3).

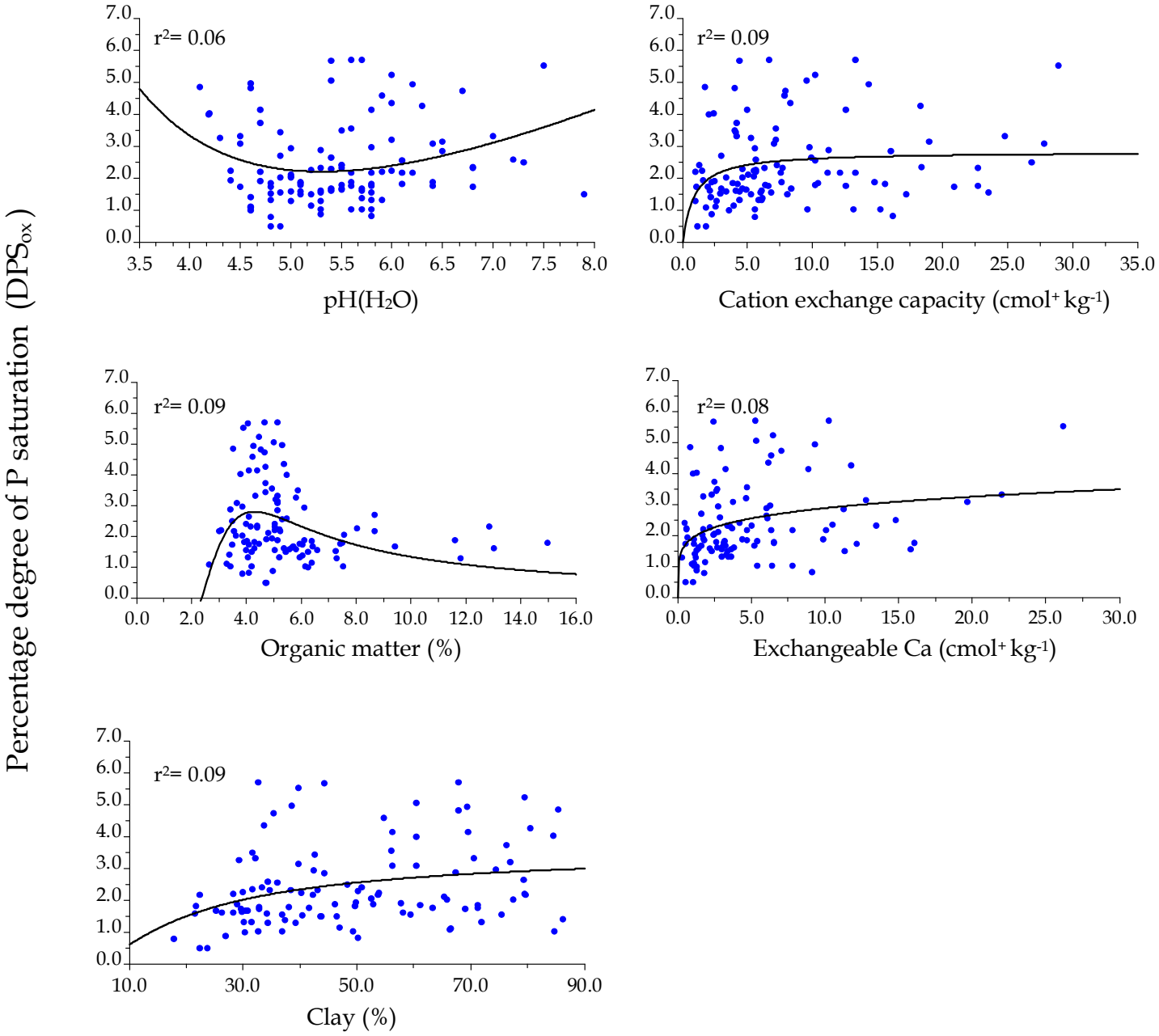


Figure 4.3: Percentage degree of P saturation (DPS_{ox}) as a function of pH(H_2O), organic matter (%), clay (%), cation exchange capacity ($cmol^+ kg^{-1}$) and exchangeable calcium ($cmol^+ kg^{-1}$) in the main soils under sugarcane of Mauritius.

This was true both when all the soil data were grouped together and when the data for the latosols and for the latosolic soils were considered separately (Table 4.5). Among the three soil P tests examined in this study, the DPS_{ox} exhibited the poorest relationship with the soil properties with none of the r^2 values being above 0.10.

Table 4.5: Correlation between DPS_{ox} (y) and pH (H_2O), organic matter, clay, exchangeable Ca and cation exchange capacity (x) of the main soils under sugarcane in Mauritius.

Soil property (x)	Data set	Regression model and coefficient data	r^2 value
pH (H_2O)	All soils	$y=a+bx+c/(x^2)$ a= -10, b= 2, c= 119	0.06
	Latosols	$y=a+bx+c/(x^2)$ a= -9, b= 1, c= 106	0.05
	Latosolic soils	$y=1/(ax+b)$ a= -0.06, b= 0.82	0.03
Organic matter (%)	All soils	$y=(a+bx)/(1+cx+dx^2)$ a= -2.9, b= 1.2, c= -0.5, d= 0.1	0.09
	Latosols	$y=a+bx+c/(x^2)$ a= 6.5, b= -0.5, c= -27.6	0.05
	Latosolic soils	$y=a+bx+cx^2$ a= 4.40, b= -0.57, c= 0.03	0.10
Clay (%)	All soils	$y=ae^{(b/x)}$ a= 3.7, b= -17.5	0.09
	Latosols	$y=a/(1+be^{-cx})$ a= 2.9, b= 434, c= 0.3	0.13
	Latosolic soils	$y=1/(ax+b)$ a= -0.01, b= 0.73	0.11
Exchangeable Ca ($cmol^+ kg^{-1}$)	All soils	$y=ax^b$ a= 1.95, b= 0.17	0.10
	Latosols	$y=ax^b$ a= 3.19, b= 0.48	0.08
	Latosolic soils	$y=1/[a+bln(x)]$ a= 0.63, b= -0.11	0.16
Cation exchange capacity ($cmol^+ kg^{-1}$)	All soils	$y=ax/(b+x)$ a= 2.85, b= 0.84	0.05
	Latosols	$y=a(1-e^{-bx})$ a= 2.93, b= 0.68	0.07
	Latosolic soils	$y=ax^b$ a= 1.43, b= 0.20	0.08

Similar to the 0.1M H_2SO_4-P and the 0.01M $CaCl_2$-P, multiple linear regression analysis again showed that the r^2 value could be improved by combining the effects of the soil properties. Thus by adding the effects of exchangeable Ca ($cmol^+ kg^{-1}$), clay (%) and organic matter (%) together, the relationship between these three parameters and DPS_{ox} may be described to some extent by the following equation:

$$DPS_{ox} = 1.461 + 0.0696 \text{ exchangeable Ca} + 0.0168 \text{ clay} - 0.0378 \text{ organic matter}; \quad r^2 = 0.16$$

As mentioned in section 4.3.3, the inclusion of either pH or CEC in the multiple regression equation is inappropriate since these soil properties are themselves correlated to exchangeable Ca. It can moreover be noted that in the multiple linear regression analysis, a lower r^2 value (0.16) was obtained for DPS_{ox} as opposed to a r^2 of 0.30 for 0.1M H_2SO_4-P and 0.49 for 0.01M $CaCl_2$-P, demonstrating clearly that DPS_{ox} is the least influenced by the soil properties.

It was found in this study that the ammonium oxalate extractable Fe and Al were higher in the latosolic soils (i.e. the immature soils) than in the latosols (Table 4.6). This finding tends to indicate that more P adsorption sites exist in the latosolic soils than in the latosols. In spite of this difference in extractable Fe and Al, the average DPS_{ox} for each soil group as shown in Table 4.6 did not vary much among the five soil groups, ranging from 2.02% in the Latosolic Brown Forest to 2.89% in the Humic Latosol.

Table 4.6: Ammonium oxalate extractable P, Fe, Al and the DPS_{ox} (mean ± SE) in the main soil groups under sugarcane in Mauritius.

Soil group (Number of samples)	**Ammonium oxalate extractable**			**DPS_{ox} (%)**
	P_{ox}	**Fe_{ox}**	**Al_{ox}**	
	mmol kg^{-1}			
Low Humic Latosol (27)	7.7 ± 0.8	124 ± 11	182 ± 29	2.72 ± 0.24
Humic Latosol (18)	9.7 ± 1.4	139 ±27	234 ± 34	2.89 ± 0.39
Humic Ferruginous Latosol (21)	7.4 ± 0.9	175 ± 27	160 ± 22	2.54 ± 0.28
Latosolic Reddish Prairie (18)	15.3 ± 1.7	360 ± 39	376 ± 67	2.45 ± 0.33
Latosolic Brown Forest (28)	14.1 ± 0.3	322 ± 7	417 ± 11	2.02 ± 0.04

4.3.5 Establishment of threshold DPS_{ox} and 0.01M $CaCl_2$-P values

As explained in section 4.1, the split line model when applied to the values of 0.01M $CaCl_2$-P and their corresponding DPS_{ox} in the 112 soils studied would indicate a change point (threshold DPS_{ox}) above which the P is not retained (or with difficulty) by the soil. The results obtained following the application of the split line model to the data of 0.01M $CaCl_2$-P and DPS_{ox} tabulated in Appendix 2 are shown in Figure 4.4.

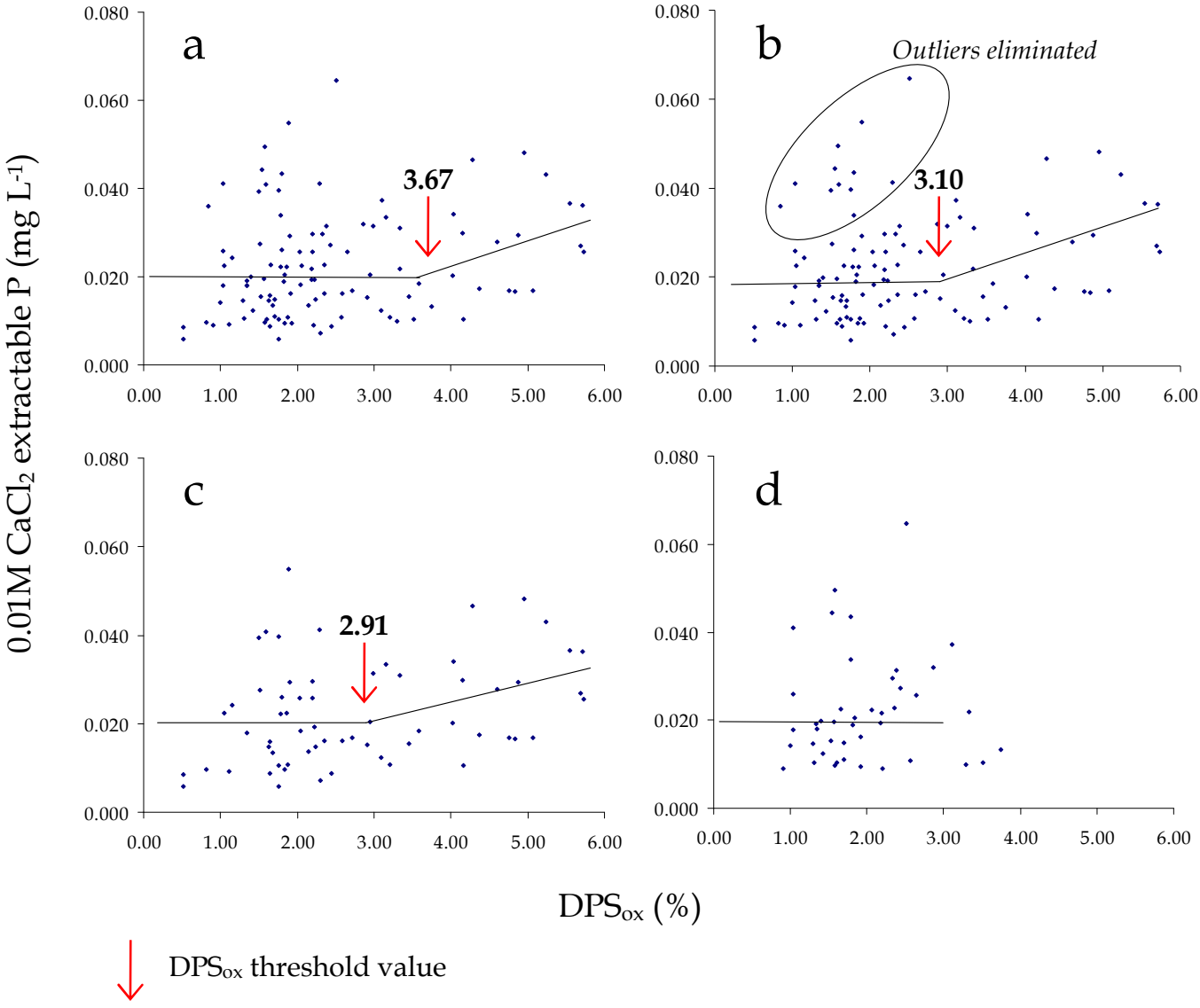


Figure 4.4: The relationship between the 0.01M $CaCl_2$ extractable P (mg L^{-1}) and the DPS_{ox} (%) when (a) data for all soils were combined as one data set, (b) after elimination of 12 outliers for the combined data set, (c) data for only latosols are considered and (d) data for only latosolic soils are used.

Thus when the data for the five soil groups were pooled together to form one data set and also when the data for the latosols are considered on their own, a horizontal line is obtained at the low DPS_{ox} values followed by a line with a positive inclination at the higher DPS_{ox}, the two lines intercepting at a change point which can be referred to as the threshold DPS_{ox} value. The change points obtained are listed in Table 4.7.

Table 4.7: Threshold DPS_{ox} and 0.01M $CaCl_2$-P values found in soils of Mauritius when the split line model technique is used.

Data set	Threshold DPS_{ox} (%)	Threshold 0.01M $CaCl_2$-P (mg L^{-1})
(a) All soils grouped together	3.67 ±0.69*	0.021 ±0.001*
(b) All soils grouped together with 12 outliers eliminated	3.10 ±0.10	0.018 ±0.001
(c) Latosols only	2.91 ±1.11	0.020 ±0.002
(d) Latosolic soils only	*Not determined*	0.019 ±0.001

* Estimate of threshold ± SE

Below that threshold DPS_{ox}, the horizontal line indicates that little P will be desorbed into the $CaCl_2$ solution, while above it, the line with the positive inclination shows that P is being retained with difficulty and environmentally significant quantities of P will begin to pass into solution. Maguire and Sims (2002) further described the threshold DPS_{ox} as the point below which only small amounts of weakly bound P exist in soils and above which the quantity of weakly bound P increases rapidly. For the latosolic soils when considered on their own, the line of positive inclination could not be established due to the paucity of DPS_{ox} value above 3.0 (Figure 4.4).

The results obtained upon applying the split line model technique to the values of DPS_{ox} and to the concentrations of P extractable in 0.01M $CaCl_2$-P have thus shown that for soil P, soils not to constitute a hazard to the freshwater sources in Mauritius, the DPS_{ox} should not exceed 3.1% and the P in 0.01M $CaCl_2$ must be less than 18 μg L^{-1}. These two values

may thus be adopted as criteria for evaluating the environmental P status of soils under sugarcane in Mauritius.

4.3.6 Establishment of the 0.1M H_2SO_4-P environmental threshold

The importance of establishing a correlation between the 0.1M H_2SO_4-P and the DPS_{ox} has been explained in section 4.1. Thus even though the DPS_{ox} is a suitable P loss risk indicator due to its strong relationship with runoff P concentration (Casson *et al.*, 2006), the measurement of the DPS_{ox}, as opposed to that of 0.1M H_2SO_4-P, is tedious and time-consuming given that firstly the extraction time is relatively long (two hours) and then three chemical parameters (P_{ox}, Fe_{ox} and Al_{ox}) have to be analysed in the resulting ammonium oxalate extract. The DPS_{ox} is therefore unlikely to be used in routine soil P testing. The 0.1M H_2SO_4 soil P test, on the other hand, is already a common procedure in agronomic soil P analysis in Mauritius.

To establish the relationship between 0.1M H_2SO_4-P and DPS_{ox}, different regression models were fitted to the experimental data obtained, firstly when data for all soils were combined together and secondly when the latosols and latosolic soils were considered separately. The various regression models ranged from linear to polynomials, exponential, power law, yield density and growth equations. The r^2 values for the various models when data for all soils were combined varied from 0.17 to 0.23 with standard errors of the order of 51.44 to 52.93 as shown in Table 4.8. No noteworthy improvements in the standard errors or in the r^2 values were obtained when the latosols and the latosolic soils were considered separately (Table 4.8).

The relationship between 0.1M H_2SO_4-P and DPS_{ox}, on the other hand, improved significantly upon elimination from the data set of the outliers shown in Figure 4.4b. The improvement was reflected in the r^2 value which rose to as high as 0.56 and in the standard errors which decreased to a mean 28.6 (Table 4.9).

Table 4.8: Relationship between 0.1M H_2SO_4-P (y) and DPS_{ox} (x) when all soils were grouped together, and when the latosols and latosolic soils were considered apart.

Regression model	Coefficient data	r^2 values	Standard error
All soils grouped together (n=112)			
$y=a+bx+cx^2+dx^3$	a= -63.6, b= 163.0, c= -52.5, d =5.5	0.23	51.44
$y=a(1-e^{-bx})$	a= 137.9, b= 0.57	0.18	52.34
$y=(a+bx)/(1+cx+dx^2)$	a= -17.6, b= 155.7, c= 1.3, d= -0.09	0.19	52.59
$y=1/(a+bx^c)$	a= 0.13, b= -0.12, c= 0.04	0.18	52.74
$y=a+bx$	a= 50.1, b= 17.8	0.17	52.87
$y=a+bx+cx^2$	a= 37.7, b= 27.9, c= -1.6	0.18	52.93
Latosols (n=66)			
$y=a+bx+cx^2+dx^3$	a= -35.9, b= 124.4, c= -39.7, d= 4.3	0.31	45.42
$y=a+bx+(c/x^2)$	a= 54.1, b= 16.2, c= -12.4	0.28	46.28
$y=1/(ax+b)$	a= -0.0018, b= 0.0163	0.27	46.34
$y=ax^b$	a= 55.9, b= 0.55	0.27	46.36
$y=ab^x$	a= 55.9, b= 0.5	0.26	46.42
$y=ae^{bx}$	a= 54.1,b= 0.19	0.26	46.41
$y=a+bln(x)$	a= 51.3, b= 49.4	0.26	46.43
$y=a+bx$	a= 41.3, b= 19.3	0.26	46.45
$y=a+bx+cx^2$	a= 45.4, b= 16.1, c= 0.5	0.26	46.82
Latosolic soils (n=46)			
$y=a+bx+cx^2$	a= -93.3,b= 169.2, c= -33.7	0.14	59.52
$y=a+(b/x)$	a= 145.6, b= -92.5	0.10	60.54
$y=a/[1+be^{-cx}]$	a= 112.8, b= 27.0, c= 2.91	0.11	60.73
$y=a+bx+(c/x^2)$	a= 156.7, b= -13.4, c= -101.7	0.11	60.78
$y=ab^{(1/x)}$	a= 157.3, b= 0.4	0.08	60.85
$y=ae^{(b/x)}$	a= 157.3, b= -1.0	0.08	60.85
$y=a(1-e^{-bx})$	a= 124.5, b= 0.8	0.08	60.93
$y=ax/(b+x)$	a= 171.7, b= 1.6	0.07	61.17
$y=a+bln(x)$	a= 63.1, b= 47.5	0.07	61.22
$y=ax^b$	a= 70.2, b= 0.4	0.06	61.60
$y=1/(a+bln(x))$	a= 0.013, b= -0.004	0.05	61.90
$y=a+bx$	a= 54.5, b= 19.2	0.05	62.07
$y=ae^{bx}$	a= 66.9, b= 0.2	0.04	62.37

Table 4.9: Regression models describing the relationship between the 0.1M H_2SO_4-P and DPS_{ox} when all soils were grouped together after elimination of 12 outliers.

Regression models	Coefficient data	Coefficient of determination, r^2	Standard error
$y=a+bx+cx^2+dx^3$	a =-7.8, b =66.5, c =-19.4, d =2.4	0.58	28.31
$y=(a+bx)/(1+cx+dx^2)$	a =-4.6x10^8, b =1.4 x10^9, c =2.3 x10^7, d =-2.8 x10^6	0.58	28.38
$y=1/(a+blnx)$	a =0.023, b =-0.010	0.56	28.43
$y=1/(a+bx^c)$	a =0.053, b =-0.031, c =0.235	0.56	28.55
$y=ab^x$	a =36.0, b =1.3	0.55	28.57
$y=ae^{bx}$	a =36.0, b =0.3	0.55	28.57
y=a+bx	a =17.34, b =23.2	0.54	29.04

Of the seven regression models listed in Table 4.9, the linear fit regression model (y=a+bx, with a =17.3, b =23.2) would most appropriately describe the relationship between 0.1M H_2SO_4-P and DPS_{ox}, given that the linear regression was statistically significant at 99% confidence interval and has the additional advantage of being the simplest regression model encountered in statistics. Moreover apart from the fact that it is easy to use, the linear regression model has a r^2 value of 0.54 which is similar to those obtained from the other six models. In the present study, the linear regression has accordingly been chosen to describe the relationship between the 0.1M H_2SO_4-P and the DPS_{ox} (Figure 4.5).

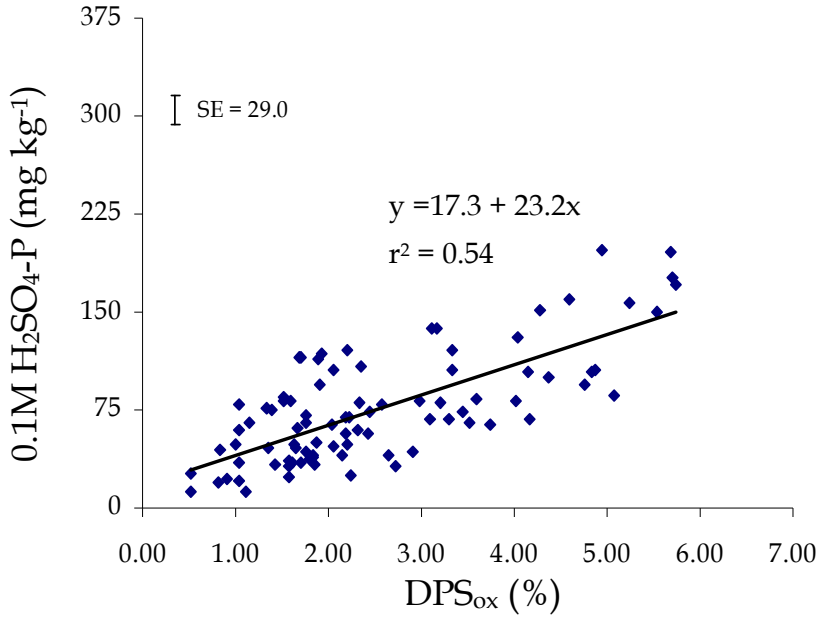


Figure 4.5: The relationship between 0.1M H_2SO_4-P (mg kg^{-1}) and the DPS_{ox} (%) for the five main soils under sugarcane in Mauritius.

Based on the relationship between DPS_{ox} (%) and 0.1M H_2SO_4 (mg kg^{-1}) in Figure 4.5 and given by the equation below:

$$0.1M\ H_2SO_4\text{-}P = 17.3 + 23.2\ DPS_{ox}\ (r^2 = 0.54);$$

a threshold DPS_{ox} of 3.10% derived in section 4.3.5 will correspond to a reading of 89 mg kg^{-1} of 0.1M H_2SO_4-P. This value of 89 mg kg^{-1} of H_2SO_4-P can henceforth be used as the environmental threshold value of P in sugarcane soils above which it becomes a hazard to freshwater sources in Mauritius. From Figure 4.5, it can further be observed that at a percentage DPS_{ox} of zero, the predicted 0.1M H_2SO_4-P would be 17 mg kg^{-1} which is P extractable from sources other than Fe_{ox} and Al_{ox}, such as organic matter.

4.4 Conclusions

Though P is recognised to be one of the major elements exerting a direct influence on the quality of surface waters and is frequently the limiting nutrient for primary productivity in many freshwater systems (Mukherjee *et al.*, 2009), the risk it actually represents to the environment in Mauritius has never been assessed prior to the initiation of this study. The present study showed that knowledge of the soil characteristics, even when interpreted with the known behaviour of P in soils, can at best only provide a very general qualitative view of the likely impact of soil P on freshwater quality. Thus on the basis of the characteristics of the soils in Mauritius, it may be inferred that, as a general rule, with their more clayey texture, lower organic matter content and higher exchangeable Ca and Mg, soils of the low rainfall regions of Mauritius, namely the Low Humic Latosol and Latosolic Reddish Prairie soils, would fix or adsorb P more extensively than the soils in the high rainfall zones and would, in so doing, effectively reduce the leaching of P through the soil profile and into groundwater systems. The capacity of the soils of the low rainfall zones to fix more P further implies that the P in those soils would be more susceptible to loss in runoff events if erosion occurs. As the average pH among the main soil groups ranges from 5.2 to 6.0, the differences in pH among the main soils are small and are unlikely to negate the higher tendency of soils in the low rainfall regions to fix more P than the soils of the wet zones, namely the Humic Ferruginous Latosols and Latosolic Brown Forest soils.

On the other hand, with the higher organic matter content impeding the fixation of P in the soils of the wet regions and coupled with a higher rainfall regime, the P in soils of the high rainfall zones will be more prone to leaching into the groundwater systems than the P in soils of the dry regions of Mauritius. This tendency towards more leaching in soils of the high rainfall areas would reduce the risk of P movement by runoff during soil erosion to contaminate into the surface waters, implying that eutrophication of the streams and river systems would be less frequently encountered in the high rainfall areas than in the dry zones of Mauritius.

Moreover with the low r^2 values obtained when the soil properties examined were correlated with the level of P extractable in 0.1M H_2SO_4, in 0.01M $CaCl_2$ or in 1M ammonium acetate solution, it may be inferred that none of the determined soil characteristics could be utilised as an indication of soil P susceptibility to transport into ground or surface waters in Mauritius. Instead the susceptibility of the soil P to mobilisation is the result of the combined effects of all soil characteristics controlling P sorption-desorption reactions in soils. The present study in applying the split-line model technique to the P extractable in 0.01M $CaCl_2$ and to the DPS_{ox} values has shown that P in the soils of Mauritius is unlikely to be mobilised so long as the DPS_{ox} does not exceed 3.10% and that amount of P be extractable from the soil lies below 20 $\mu g\ L^{-1}$ in a 0.01M $CaCl_2$ extractant.

More importantly, the present study showed that the soil P test using 0.1M H_2SO_4 as extractant, which is routinely used to assess the availability of P to sugarcane in soils of Mauritius, can also be adopted as an environmental soil P test. In fact the work done has revealed that the environmental threshold of P by 0.1M H_2SO_4 extraction is 89 mg kg^{-1}, which does not exceed by far the agronomic soil P threshold of 80 mg kg^{-1} for sugarcane in Mauritius. The present study has therefore paved the way for the P status of Mauritian sugarcane soils to be evaluated from the freshwater protection perspective.

5 Evaluation of the environmental P status of Mauritian sugarcane soils using 0.1M H_2SO_4 extractable P values

5.1 Introduction

Sugarcane is currently cultivated on 69,000 hectares of land in Mauritius. The intensive use of P fertilisers during the past 50 years to remove P supply as a limitation to productivity has resulted, as discussed in Chapter 3, in a general build-up of the P status of many sugarcane soils in Mauritius. Although most soils fix the P strongly, only very small amounts of the P need to be lost from soil, as mentioned in section 1.2, to create a P concentration in fresh water ecosystems likely to cause environmental problems associated with eutrophication. Therefore, though it is vital that the productive potential of the existing sugarcane lands in Mauritius is maintained, that potential must also be in harmony with the need to safeguard the environment. This inevitably implies the development of an agro-environmental soil P test and the establishment of a soil P threshold above which the P in the soil would result in unacceptable P enrichment of agricultural runoff.

In showing that the same soil P test routinely used to assess soil P available to sugarcane in Mauritius is also valid as an environmental soil P test and that the environmental threshold of P is 89 mg kg^{-1} as extracted by 0.1M H_2SO_4, the present study has made possible an evaluation of the P status of Mauritian sugarcane soils from the freshwater protection perspective. This chapter therefore describes how the soil test P data obtained by extraction with 0.1M H_2SO_4 has been used to provide a picture of the environmental P status of sugarcane soils in Mauritius.

5.2 Categorisation of the P status of Mauritian sugarcane soils into four classes

The results obtained in section 4.3.5 showed that P will be weakly retained by soils when the percentage degree of P saturation as determined by ammonium oxalate (DPS_{ox}) rises above 3.10 ± 0.10. This DPS_{ox} should thus not be exceeded for the soil P status to be considered safe and sound to the environment, and as explained in section 4.3.6, it is equivalent to 0.1M H_2SO_4 extractable P values ranging from 85 to 95 mg kg^{-1}. Accordingly

soils with this range of P values can be considered to be safe for the environment and based on this interpretation the soils under sugarcane in Mauritius, from the freshwater protection viewpoint, may be divided into the four classes shown in Table 5.1.

Table 5.1: Categorisation of P status of Mauritian sugarcane soils into four environmental classes.

Environmental class	Soil P test range *0.1M H_2SO_4-P (mg kg^{-1})*	Environmental description
I	P < 85	Sound
II	85 ≤ P < 95	Safe
III	95 ≤ P < 125	Unsafe
IV	P ≥ 125	Unacceptable

5.3 Environmental P status of Mauritian sugarcane soils

As mentioned in section 3.3.3.3, sugarcane is grown by planting cane setts which is harvested 15 to 18 months later to provide the plant cane. The regrowth (ratoon) is in turn harvested 12 months later. The crop is ratooned repeatedly thereafter until the yield declines to such an extent that replanting becomes worthwhile. In general, a field is only replanted every seven to eight years, that is, after a plant cane and six or seven ratoons (i.e. a crop cycle). Moreover, it is a current practice in Mauritius to apply P fertilisers in the furrows only at planting. Thus to be able to determine the evolution of the P status of the sugarcane soils in Mauritius over one crop cycle of seven or eight years the soil P test data of 1997/1998 were compared with those of 2005/2006.

Application of the criteria set in Table 5.1 to the soil P test data of the fields replanted in 1997/1998 showed that 58% of the soils were environmentally sound and safe and did not represent any hazard to freshwater quality in Mauritius (Figure 5.1). As much as 42% of the sugarcane fields in 1997/1998 had from the environmental viewpoint unacceptably high levels of P (P ≥ 95 mg kg^{-1}) in the soils. Examination of the soil test P data for the fields replanted in 2005/2006 using the same set of criteria in Table 5.1, confirmed that current recommendations on P management of the sugarcane need to be revisited since

the number of fields with unacceptably high levels of P (P ≥ 95 mg kg^{-1}) has risen to 53% (from 42%) in just one crop cycle of sugarcane. Concomitantly sugarcane fields with a P status that is environmentally sound or safe decreased to 47% (from 58%) over that same seven to eight year period (Figure 5.1).

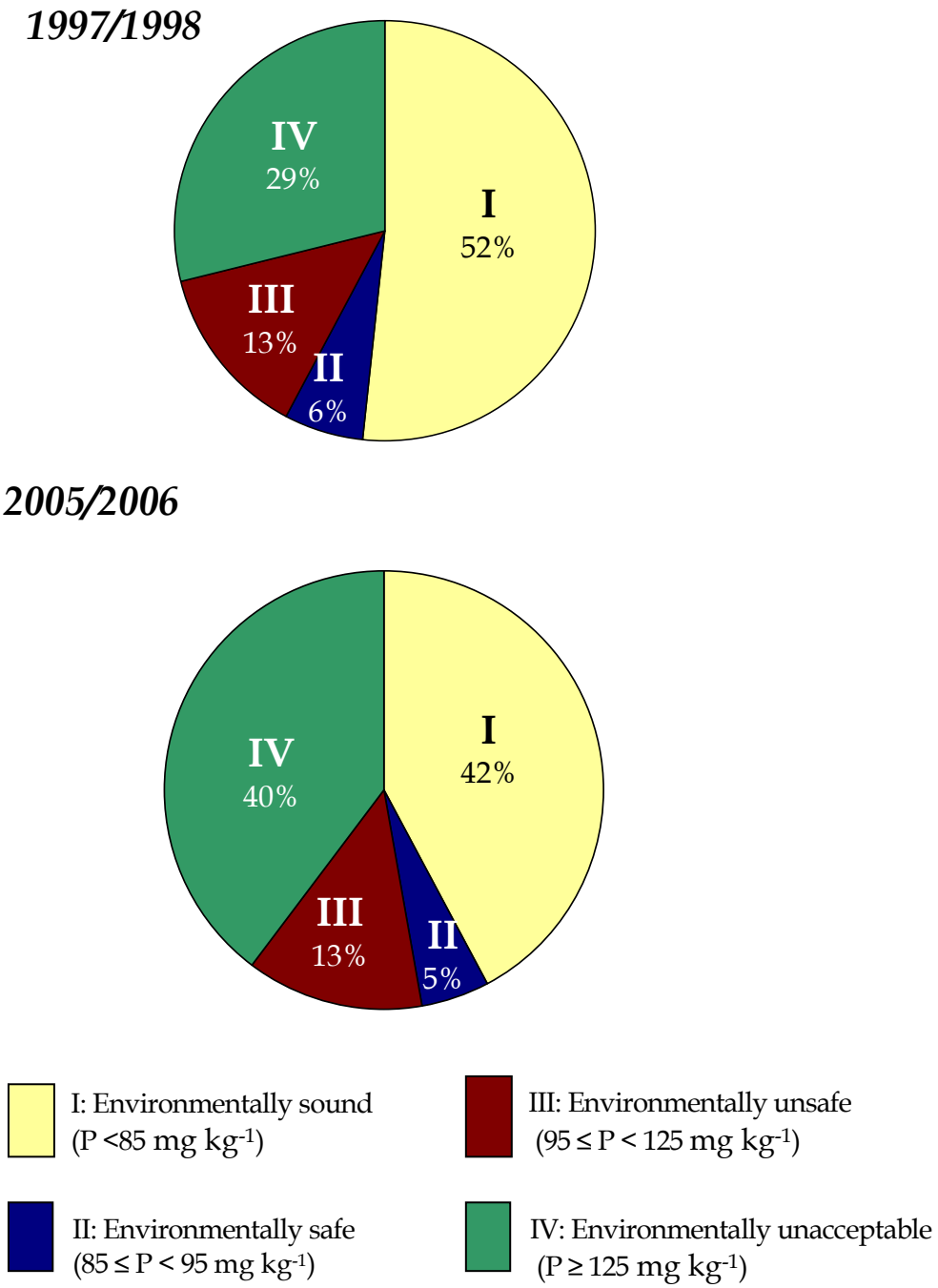


Figure 5.1: Evolution of environmental P status of sugarcane soils in Mauritius over one crop cycle (from 1997/1998 to 2005/2006).

5.4 Environmental P status of sugarcane soils when managed by large and small planters

A closer analysis of the soil test P data showed that in 1997/1998, large planters had 62% of their land that was environmentally sound and safe while 54% of the small planters' land fell within under those two environmental classes (Figure 5.2). Correspondingly, large planters had 39% of their lands with unsound and unacceptably high P levels ($P \geq 125$ mg kg^{-1}) as compared to 46% for small planters. This higher amount of land of small planters with an environmentally unacceptable P status may to some extent be explained by the fact that prior to 1997 fewer small planters (unlike the large planters) had recourse to soil P testing before replanting and fertilisation of their fields. Instead fertilisation of sugarcane by small planters was mostly based as explained in section 3.3.3.4 on the maintenance philosophy, that which calls for the complete replacement of the amount of P removed by the preceding crop with no recognition of the capacity of the soil to supply part or all of the P needs of the sugarcane. Fertilisation of sugarcane with P by large planters was based even then (though not entirely) on soil P test results (sufficiency philosophy). Apart from this difference in P fertilisation philosophy, the similar pattern in the partitioning of their sugarcane fields into environmentally sound, safe, unsafe and unacceptable P status is an indication that P management of sugarcane by the small planters differed little from that by the large planters in terms of mode and time of P application, forms of P fertilisers used and so on. For both large and small planters, either the fields had in 1997/1998, as well as in 2005/2006, an environmentally sound P status or an environmentally unacceptable P level. For both planter groups, few fields (<10%) had an environmentally safe ($85 \leq P < 95$ mg kg^{-1}) soil P status.

The similarity between the large and small planters in their P management of sugarcane fields, particularly when as from 1997 the small planters also had easy access to soil P testing, could further be seen in the near identical evolution of the environmental P status of their fields from 1997/1998 to 2005/2006 (Figure 5.2). For both planter groups the only significant change in the environmental P status of their fields was a reduction in the extent of their environmentally sound fields to increase the number of fields with an unacceptable soil P status.

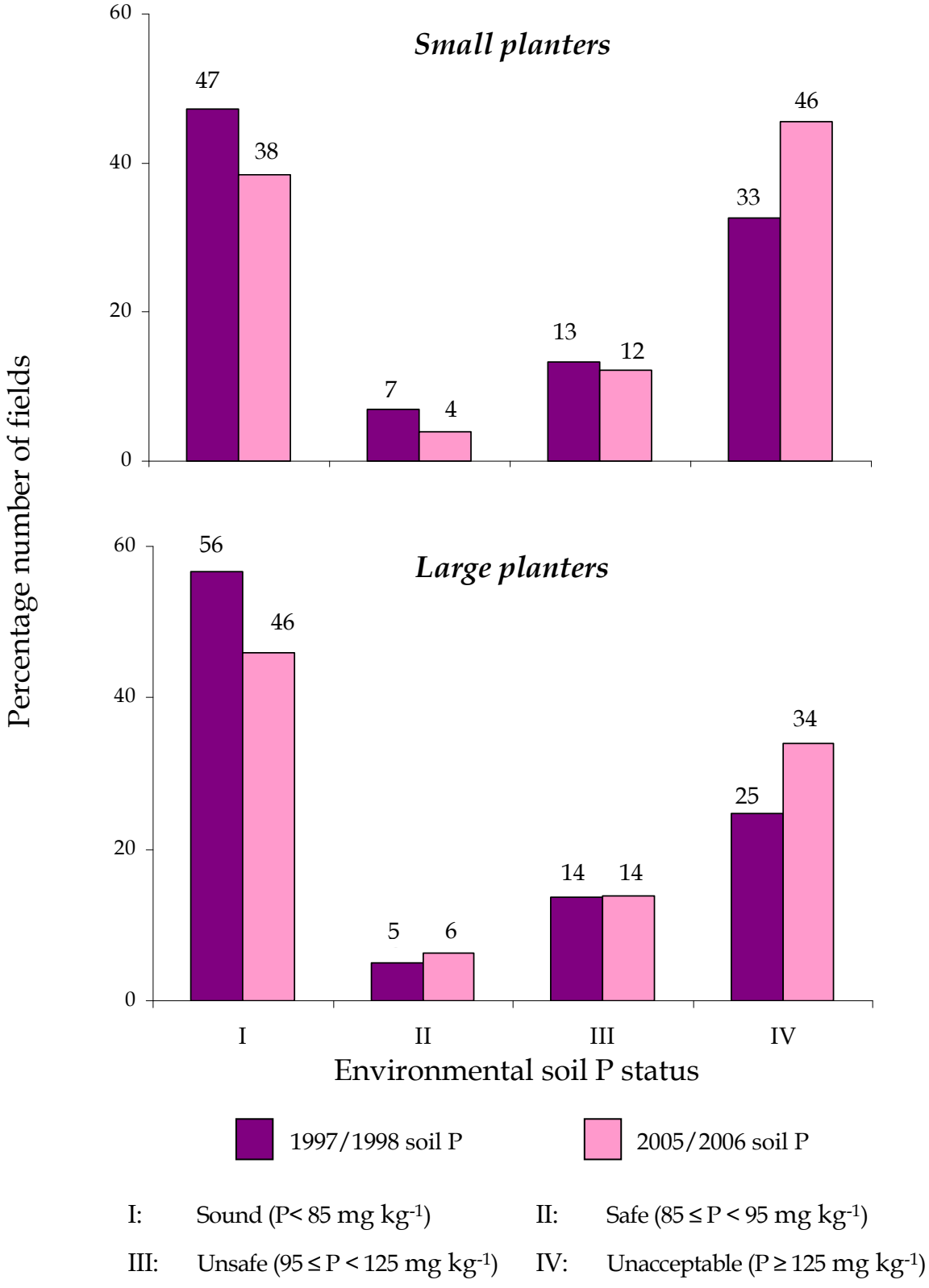


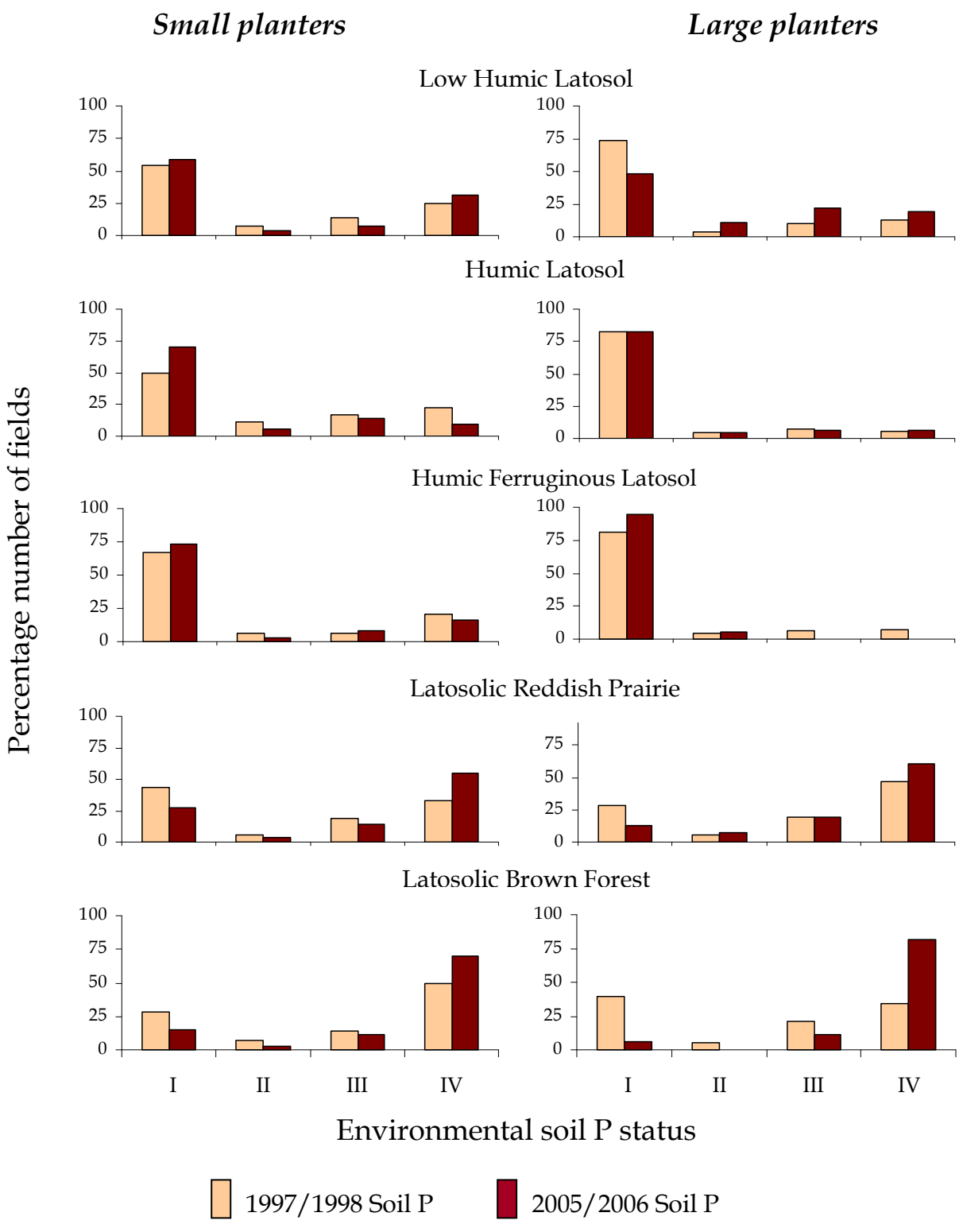
Figure 5.2: Environmental soil P status of fields managed by small and large sugarcane planters in 1997/1998 and in 2005/2006.

5.5 Environmental P status of the five main soil groups under sugarcane in Mauritius

As already mentioned at the end of section 3.3.1, sugarcane is cultivated mainly on five soil groups in Mauritius. A scrutiny of the environmental soil P status of the sugarcane fields in those five soil groups shows that with the similar P management practices of the sugarcane by the large and small planters, the P profile in each of the soil groups was not influenced by the category of planter farming it (Figure 5.3).

Since the P profile of each of the main soil groups tends to be independent of the category of planter growing the sugarcane, the current environmental P status of the sugarcane soils in Mauritius, as can be deduced from the soil P test carried out in 2005/2006, may be discussed without any consideration of whether the farmer was a large land holder or a small one. The soil P test data for the large and small planters can therefore be pooled together for evaluating the environmental soil P status of the different soil groups in Mauritius.

In so doing it can be seen that in 2005/2006, as shown in Figure 5.4, the majority (74%) of sugarcane fields with an environmentally unacceptable P status were located on latosolic soils (i.e. Latosolic Reddish Prairie and Latosolic Brown Forest soils). Moreover from 1997/1998 to 2005/2006 a significant rise in the number of fields with environmentally unacceptable P levels was noted in the Latosolic Brown Forest soils (31 to 42%) which are found in the high rainfall zones of Mauritius (> 3,000 mm annual rainfall). The sugarcane fields on the Humic Ferruginous Latosol soils which are located in more or less the same high rainfall zone as the Latosolic Brown Forest soils have on the other hand mostly an environmentally sound P status irrespective of whether those fields were farmed by the small or large planters (Figure 5.3).



I: Sound (P< 85 mg kg^{-1}) II: Safe (85 ≤ P < 95 mg kg^{-1})

III: Unsafe (95 ≤ P < 125 mg kg^{-1}) IV: Unacceptable (P ≥ 125 mg kg^{-1})

Figure 5.3: The environmental P status in 1997/1998 and in 2005/2006 of the five main soil groups under sugarcane in Mauritius when farmed by the large and small planters.

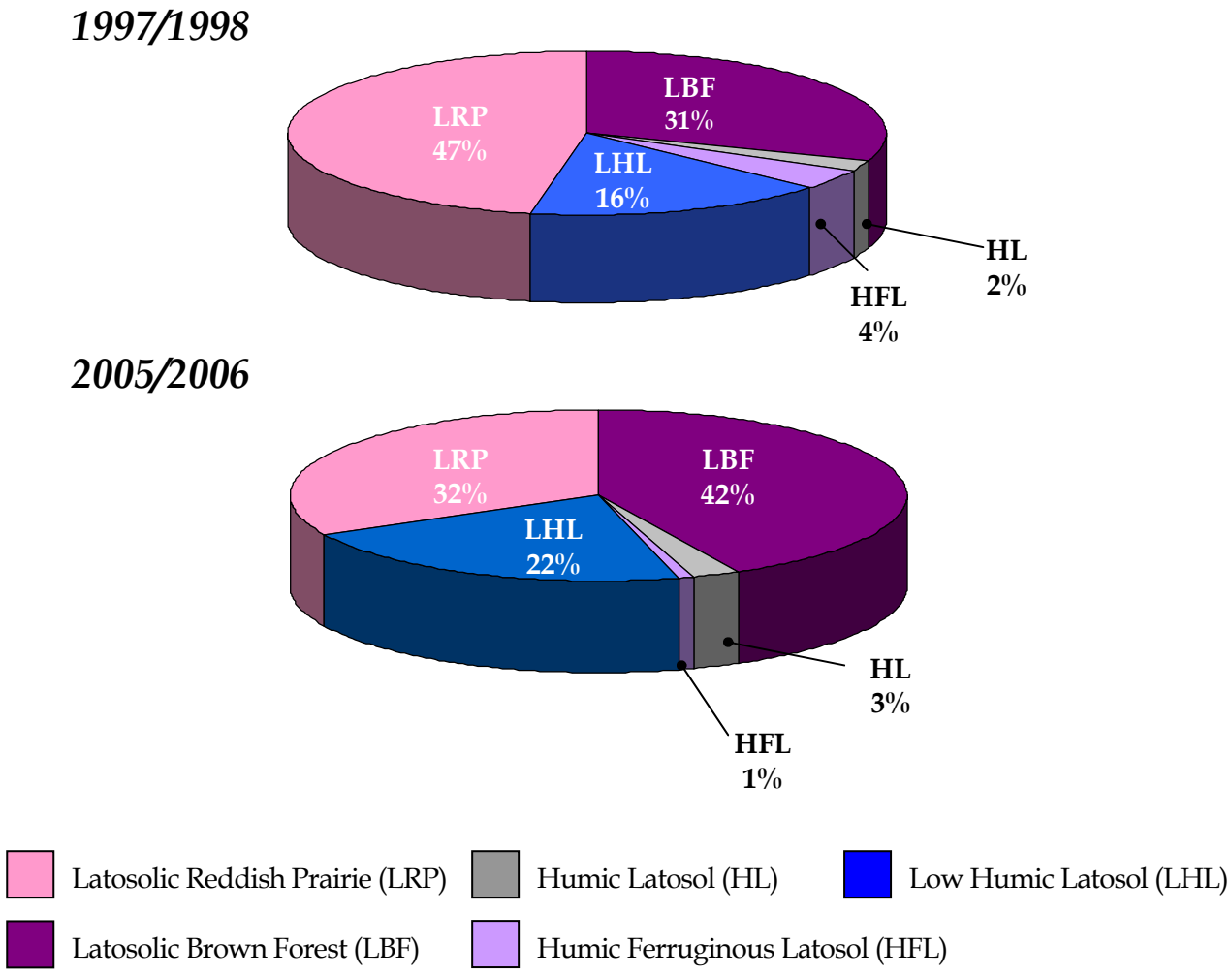


Figure 5.4: Distribution of the fields with environmentally excessive P level (P ≥ 95 mg kg^{-1}) among the five main soil groups.

As P management of sugarcane in Mauritius does not differ from one soil group to another, the soil test P data examined show a greater tendency of P accumulation in the latosolic soils, implying that corrective P management measures to protect freshwater sources must be targeted towards sugarcane fields in the latosolic soils, especially those with Latosolic Brown Forest soils having environmentally unacceptable P levels (P ≥ 125 mg kg^{-1}) because those soils are located in the high rainfall areas of Mauritius (> 3,000 mm annual rainfall). Though in the Latosolic Reddish Prairie soils there is also a high percentage of fields with an excessive amount of soil P (P ≥ 95 mg kg^{-1}), these soils are located in the low rainfall regions of Mauritius (< 1,500 mm annual rainfall) where surface runoff events are less prone to occur.

5.6 Conclusions

Interpretation of the soil P test data obtained by 0.1M H_2SO_4 extraction shows that the environmental P status of the sugarcane soils is far from rosy. Indeed in 2005/2006 more than 50% of the Mauritian sugarcane soils had an unsafe or unacceptable soil P status from the freshwater protection perspective. Though any loss of P from the soil may not be of economic importance to the sugarcane planters, the deterioration in water quality that follows from eutrophication can have very significant offsite economic impacts including the cost for purification of drinking water, and preservation of nature reserves, as well as deterioration in recreational quality and damage to commercial fishing.

As indicated by the 2005/2006 soil test P data when compared to those obtained in 1997/1998, if current recommendations on P management of sugarcane are leading to a deterioration of the environmental P status of the soils and nothing is done, the soil P status can be expected to continue to worsen in the years to come. An analysis of the soil test P data moreover showed that since a higher distribution of the soils with an environmentally excessive P ($P \geq 95$ mg kg^{-1}) occurred predominantly in the Latosolic Reddish Prairie (32%) and in the Latosolic Brown Forest soils (42%), revision of P management practices or implementation of other corrective measures such as creation of riparian zones should primarily be directed towards those two soil groups with emphasis on the Latosolic Brown Forest soils because they are located in the high rainfall areas. This revision of P management practices will be greatly enabled by the fact that the P status of the different soil groups is not dependent on whether the land belongs to small or to large planters.

6 General conclusions and recommendations for further studies

6.1 Introduction

Phosphorus, the third most important element in crop production, has been in the limelight of Mauritian agriculture ever since organised research on sugarcane began in 1893 with the creation of the *Station Agronomique*. The research that was done on P has since been reviewed by Wong You Cheong (1967) within the framework of a PhD thesis. More than four decades have elapsed since that review which was written when the consensus opinion in the scientific world was that P use in agriculture has little or no effect on the quality of freshwater system.

The damaging effect which agricultural P can have on water quality has since been brought to light and extensively researched. This study, while also reviewing the history of P fertiliser usage in Mauritius and the more recent research on P especially in sugarcane, has provided apart from an update on the agronomic P status of the sugarcane soils, an assessment of the soil P status from the environmental viewpoint. A more global picture of the impacts of P usage in sugarcane in Mauritius has therefore emerged with the adding of an environmental dimension to the agronomic role of the P. Conclusions that can be drawn from that global picture of P in the sugarcane soils of Mauritius are presented in this Chapter. The way forward from this study is a proposed suggestion for future studies.

6.2 General conclusions

The history of P fertiliser usage in Mauritius has shown that from an annual consumption averaging 810 tonnes P_2O_5, mainly in the form of insoluble mineral fertilisers (i.e. guano/rock phosphates) during the first half of the 20th century, the amount of P applied to sugarcane fields reached a peak of 5,850 tonnes P_2O_5 in the 1970s. This intensive use of P fertilisers has created, prior to this study, a general belief among the sugarcane planting community that the soils in Mauritius have invariably attained a highly satisfactory soil P status and specific attention for this important plant nutrient is no longer warranted.

Instead P management in sugarcane has been practised as a matter of routine to maintain the perceived good P status of the soils.

This study has brought to light that in spite of the liberal applications of P in the form of guano/ rock phosphates (a cheap source of P at that time) which were recommended in the 1960s and in spite of the extensive research which has been done in Mauritius on the P nutrition of sugarcane and of the voluminous knowledge on P that has accrued from studies undertaken elsewhere, much remains to be done to attain the objective of not having P deficient sugarcane soils.

Indeed irrespective of whether the sugarcane fields were managed by large or small planters, as much as 36% of the soils in Mauritius were still deficient in P in 2005/2006 and would require P fertilisation to obtain an optimum sugarcane production. This high amount of P deficient soils persisted in spite of the fact that the maintenance philosophy, which did not favour mining of the soils for P, has until the end of the 1990s been favoured in P fertilisation.

The need to revisit P fertilisation management in sugarcane in Mauritius cannot be more glaring from the findings of this study when it is shown that P fertilisation has preferentially favoured the occurence of excessive P levels in the soils instead of simply increasing the area of the sugarcane land with agronomically optimum P level. Soils with an excess P ($P \geq 125$ mg kg^{-1}) rose from 29% in 1997/1998 to 40% in 2005/2006 after just one crop cycle of sugarcane while those with an optimum P status ($85 \leq P < 95$ mg kg^{-1}) have tended to stay constant (6%) over that same time period.

Moreover in showing that the 0.1M H_2SO_4 extraction, which was specifically developed in the late 1980s for sugarcane P fertiliser recommendations, is also suitable for an environmental risk assessment of P loss potential from sugarcane fields, this study has demonstrated clearly that the agronomic objectives in P management for sugarcane production in Mauritius tend to be incompatible with the environmental aims of protecting the freshwater resources in Mauritius. Thus the 52% of sugarcane soils that

contained more than 100 mg kg^{-1} 0.1M H_2SO_4-P in 2005/2006 may be desirable from the standpoint of sugarcane production, but are on the other hand not acceptable from the environment protection perspective. In fact with the agronomic threshold range of 80 mg kg^{-1} to 100 mg kg^{-1} P overlapping the environmental P threshold range of 85 to 95 mg kg^{-1}, the present study indicates that soils in Mauritius that are agronomically deficient for sugarcane cultivation are on the contrary safe and sound from the environment protection viewpoint and vice versa (Figure 6.1).

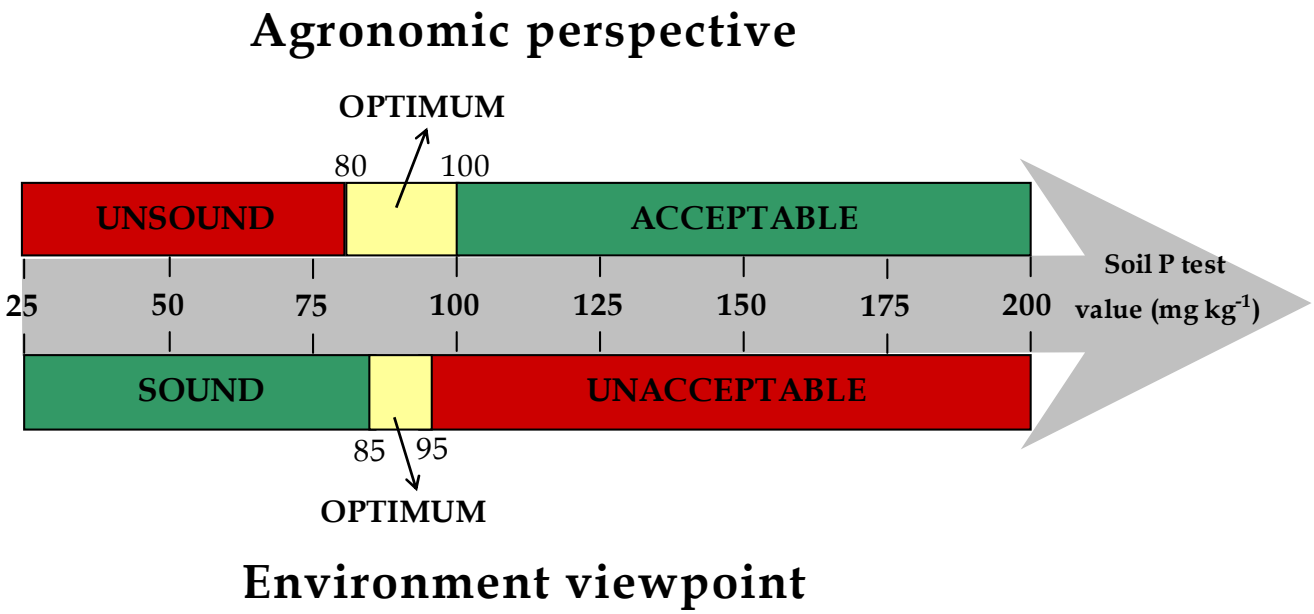


Figure 6.1: Interpretation of the P status of sugarcane soils in Mauritius from the agronomic and environmental perspectives.

Soils with a P status that is suitable for both production of sugarcane and for preservation of freshwater quality in Mauritius are limited to the 5% (2005/2006) of sugarcane fields with a narrow range of 85 to 95 mg kg^{-1} P. Consequently a revamping of P management practices in Mauritius, which is necessary to reduce the extent of P deficient soils for sugarcane growth, will in all likelihood concomitantly lead to a reduction in sugarcane areas with an environmentally sound soil P status. The very narrow range of soil P levels ($85 \leq P < 95$ mg kg^{-1}) that denotes both an agronomically sound and an environmentally safe P status in fact leaves few options available for modifying P management in sugarcane to the simultaneous satisfaction of both the agronomists and the

environmentalists. Other measures which have little to do with managing P status of soils such as the creation of riparian zones, the introduction of buffer crops (e.g. *vetiveria*) on the edges of sugarcane plantations or even terracing of sloping fields may prove to be more effective in minimising the risk of P transfer from sugarcane fields to freshwater systems.

The present study further shows that replacing sugarcane by other crops is not an option for reducing the movement of P from arable land to freshwater sources. From this perspective, the results obtained in fact tend to confirm that sugarcane is environmentally clean as its P needs are met in soils containing only 80ppm P extractable in 0.1M H_2SO_4. At this soil P level, the P does not constitute a hazard to freshwater sources since it is below the environmental threshold of 89 mg kg^{-1} of extractable P in 0.1M H_2SO_4. On the other hand, with potato for instance, the P needs of the potato cannot be met unless P extractable by 0.1M H_2SO_4 is above 175 mg kg^{-1} of soil. Thus substituting sugarcane by potato in Mauritius will imply an even more intensive P fertilisation to raise the soil P status to 125 mg kg^{-1} of P, a level where the P as shown in this study constitutes a significant hazard to freshwater sources in Mauritius.

Finally, this study has extended the scope of the current agronomic soil test P using 0.1M H_2SO_4 as an extractant into an agro-environmental soil P test. Besides the advantage of requiring no separate extraction or additional infrastructure for evaluating the agronomic and environmental P status of the same soil sample, the agro-environmental soil test is a step ahead towards maintaining a sustainable sugarcane industry and a clean environment in Mauritius.

6.3 Recommendations for further studies

This study has highlighted a rapid and simple soil P test that can be adopted not only to increase the efficiency of sugarcane production in Mauritius, by accurately predicting how much fertiliser P must be applied to the soil, but also to protect the freshwater ecosystems by predicting the potential risk of that soil P to water quality. The soil P test alone will however unfortunately provide only an incomplete assessment of the risk which the agricultural P represents to freshwater sources.

Indeed as indicated by Sharpley and Tunney (2000), adjacent fields having similar soil test P levels but different susceptibilities to surface runoff and erosion due to contrasting topography and management, may have substantially different P loss potential. Most of the P exported from an agricultural watershed in fact comes from only a small part of the landscape during high rainfall events. For P to represent an environmental problem, there must therefore be not only a source of P (i.e. high soil test P levels or fertilizer P applied), the P must in addition be transported by leaching, runoff or erosion. Problems can only occur where these two factors come together (Gburek *et al*., 2000). A high P source with little opportunity for movement, while it may be a waste of resource, will not constitute an environmental threat to fresh water ecosystems. Likewise, a situation where there is a high vulnerability for transport, but no source of P to move, is also of little threat to the surface waters. Hence to know the potential hazard of the soil P to the freshwater ecosystems, information must be obtained on the transport processes that markedly influence the movement of P from soil to water. Since surface runoff and erosion are the main mechanisms by which P is exported from agricultural lands in Mauritius (Ng Kee Kwong *et al*., 2002), future studies must therefore be aimed at the measurements of surface runoff and erosion and at establishing the conditions under which they occur.

In addition, as the export of P in runoff occurs in particulate and dissolved forms, and as particulate P includes P associated with soil particles and organic matter eroded during flow events, measurements of runoff and erosion must also imply determination of sediment and the different forms of P in the runoffs generated either by rainfall simulation or under natural conditions in watersheds.

Furthermore to fully characterize the risk of soil P transfer to surface waters, it is not sufficient to simply integrate soil P test data with the transport processes and information on P management on a *field scale*. A comprehensive P management strategy must also address down-gradient water quality impacts because this is where the success of P management is evaluated. Further studies must therefore also be directed towards an integration of effects at *field scale* where specific P management practices are implemented to reflect results at the *watershed scale*.

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APPENDIX 1: Characteristics of soils selected for the study on the 'Evaluation of the P status of sugarcane soils in Mauritius using agronomic and environmental criteria'

Soil group and reference code	pH	OM (%)	Particle-size (oven-dried basis)					CEC	K	Na	Ca	Mg
	(H_2O)	Oven-dried basis	Clay (%)	Total sand (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	$cmol^+ kg^{-1}$				
Low Humic Latosol *(Humic Nitosol)* *												
97/41	5.6	3.0	79.7	8.7	3.0	5.7	11.6	7.6	0.65	0.26	4.72	1.93
97/42	5.4	4.1	79.3	7.2	1.1	6.2	13.4	9.9	0.35	0.44	6.06	3.04
97/47	4.6	3.4	86.2	4.7	1.4	3.3	9.1	2.2	0.28	0.08	1.17	0.67
97/48	5.9	3.1	79.5	8.0	1.5	6.5	12.5	5.7	0.84	0.23	1.71	2.89
97/49	5.7	3.4	84.7	5.2	1.2	4.0	10.1	9.6	1.35	0.08	5.43	2.74
97/53	6.2	3.6	42.2	30.6	15.9	14.7	27.2	11.2	0.67	0.11	6.33	4.07
97/58	6.2	4.3	69.3	14.1	5.0	9.1	16.6	14.3	0.74	0.19	9.30	4.07
97/59	5.8	3.8	74.4	10.3	8.6	1.7	15.3	9.8	0.32	0.34	6.29	2.81
97/61	6.3	4.7	80.5	7.6	1.9	5.7	11.9	18.3	1.07	0.37	11.81	5.03
97/73	6.1	3.9	49.7	24.8	9.8	15.0	25.4	15.6	0.25	0.30	5.43	9.63
00/4	4.6	2.7	66.4	15.7	2.1	13.6	18.0	1.8	0.21	0.15	0.97	0.48
00/5	5.8	4.1	50.2	26.4	5.6	20.8	23.4	16.1	0.81	0.48	9.11	5.75
00/34	7.9	4.2	43.6	34.0	14.0	20.1	22.4	17.2	0.62	0.64	11.34	4.62
00/59	4.5	3.7	60.4	19.2	10.5	8.6	20.3	7.1	0.43	0.18	3.76	2.68
00/60	5.3	3.4	67.3	17.3	10.2	7.1	15.4	11.3	0.39	0.83	6.06	3.98
00/76	6.8	3.5	69.0	11.8	9.8	2.0	19.1	20.9	0.78	0.53	12.18	7.37
00/77	4.2	5.5	60.5	14.8	8.5	6.3	24.8	2.1	0.30	0.22	1.06	0.47
00/84	6.0	5.1	76.9	8.1	2.2	5.9	15.0	7.2	0.40	0.32	4.62	1.87
00/100	4.9	8.7	90.6	3.1	0.7	2.3	6.3	3.0	0.07	0.39	1.62	0.89

* Soil group as per FAO classification (Arlidge and Wong You Cheong, 1975).

Soil group and reference code	pH	OM (%)	Particle-size (oven-dried basis)					CEC	K	Na	Ca	Mg
	(H_2O)	Oven-dried basis	Clay (%)	Total sand (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	$cmol^+ kg^{-1}$				
Low Humic Latosol *(Humic Nitosol) **												
00/108	5.1	4.0	61.1	18.0	4.1	13.9	20.9	10.4	0.25	0.42	4.69	5.04
00/115	4.9	3.8	77.5	7.4	1.8	5.7	15.1	3.4	0.31	0.33	1.68	1.05
MSIRI 853/08	4.2	3.8	84.6	5.3	1.5	3.8	10.1	2.4	0.44	0.22	1.31	0.42
MSIRI 855/08	4.7	4.4	69.5	8.0	0.9	7.1	22.5	5.0	0.25	0.28	3.23	1.24
80/12	6.5	5.1	44.2	30.2	10.1	20.2	25.6	16.0	0.43	0.72	11.26	3.59
80/76	5.9	4.2	54.7	20.3	5.1	15.2	25.0	7.9	0.25	0.17	6.36	1.09
80/85	6.0	4.5	79.4	5.8	1.2	4.6	14.7	10.2	1.12	0.25	6.45	2.43
80/119	5.8	5.0	75.4	10.2	4.5	5.7	14.4	23.6	0.28	0.55	15.84	6.90
Mean value	5.6	4.2	68.8	14.0	5.3	8.7	17.3	10.0	0.51	0.34	5.92	3.21
Standard deviation	0.9	1.1	14.1	8.8	4.4	5.8	5.8	6.1	0.32	0.19	4.00	2.34
Standard error	0.2	0.2	2.7	1.7	0.9	1.1	1.1	1.2	0.06	0.04	0.77	0.45

Soil group and reference code	pH	OM (%)	Particle-size (oven-dried basis)					CEC	K	Na	Ca	Mg
	(H_2O)	Oven-dried basis	Clay (%)	Total sand (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	$cmol^+ kg^{-1}$				
Humic Ferruginous Latosol *(Humic Acrisol) **												
97/19	6.0	5.2	40.2	28.8	14.6	14.2	31.0	5.5	0.23	0.15	3.68	1.41
97/26	5.5	5.0	33.3	29.6	16.5	13.1	37.1	1.3	0.19	0.19	0.49	0.44
97/66	4.7	5.0	28.3	39.6	28.5	11.0	32.1	1.0	0.09	0.04	0.58	0.30
97/72	6.1	5.3	36.1	41.3	30.6	10.7	22.7	10.2	0.18	0.22	6.11	3.70

Soil group and reference code	pH	OM (%)	Particle-size (oven-dried basis)					CEC	K	Na	Ca	Mg
	(H_2O)	Oven-dried basis	Clay (%)	Total sand (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	$cmol^+ kg^{-1}$				
Humic Ferruginous Latosol *(Humic Acrisol)* *												
00/95	5.5	5.7	30.8	38.1	22.0	16.1	31.1	3.0	0.23	0.24	1.61	0.89
00/72	4.8	4.7	23.8	40.3	17.6	22.7	35.9	1.1	0.06	0.23	0.55	0.30
00/73	4.9	4.7	22.3	44.4	24.3	20.0	33.3	1.8	0.11	0.18	1.07	0.43
00/74	4.5	4.1	29.6	31.4	14.3	17.1	39.0	1.1	0.08	0.21	0.54	0.25
00/81	5.7	5.4	28.2	36.3	18.9	17.4	35.5	2.1	0.11	0.22	1.43	0.35
00/96	4.8	6.1	32.9	36.7	21.0	15.8	30.3	2.0	0.27	0.30	1.08	0.31
00/97	4.7	4.7	57.7	24.5	13.4	11.0	17.9	2.5	0.13	0.27	1.73	0.36
00/99	5.8	4.3	21.7	40.2	22.8	17.4	38.1	4.2	0.10	0.24	3.18	0.69
00/118	5.4	5.0	60.5	16.9	10.0	6.9	22.7	9.5	0.24	0.27	5.31	3.72
00/119	6.0	5.4	33.6	31.6	8.4	23.1	34.8	8.3	0.26	0.34	6.16	1.52
00/120	5.8	4.1	56.3	20.1	6.6	13.5	23.6	12.6	0.42	0.43	8.87	2.85
MSIRI 860/08	5.1	5.6	21.6	42.5	21.3	21.2	35.9	3.3	0.94	0.22	1.40	0.77
MSIRI 901/08	4.3	5.8	29.3	31.1	17.3	13.8	39.7	5.3	0.06	0.18	1.71	3.30
MSIRI 959/08	5.5	5.9	31.6	34.9	17.0	17.8	33.5	4.0	0.37	0.25	2.69	0.69
80/32	7.0	5.1	32.2	32.7	15.5	17.2	35.0	24.8	0.52	0.21	22.01	2.07
80/98	6.1	8.7	22.3	29.7	15.6	14.1	48.0	12.1	0.32	0.22	10.05	1.53
ACIAR 1	6.7	4.7	35.4	37.9	26.5	11.4	26.7	7.9	0.11	0.11	7.07	0.60
Mean value	5.5	5.3	33.7	33.7	18.2	15.5	32.6	5.9	0.24	0.22	4.16	1.26
Standard deviation	0.7	1.0	11.4	7.2	6.3	4.2	6.9	5.7	0.20	0.08	5.01	1.18
Standard error	0.2	0.2	2.5	1.6	1.4	0.9	1.5	1.3	0.04	0.02	1.09	0.26

Soil group and reference code	pH	OM (%)	Particle-size (oven-dried basis)					CEC	K	Na	Ca	Mg
	(H_2O)	Oven-dried basis	Clay (%)	Total sand (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	$cmol^+ kg^{-1}$				
Humic Latosol *(Humic Nitosol) **												
97/18	5.4	4.07	44.2	27.1	10.6	16.5	28.7	4.4	0.51	0.15	2.43	1.33
97/45	4.7	4.71	76.3	9.1	2.9	6.2	14.7	4.2	0.40	0.11	2.47	1.18
97/46	5.3	4.28	58.1	17.2	3.6	13.6	24.7	4.1	0.26	0.26	2.69	0.89
97/52	5.5	4.17	38.3	30.3	8.3	21.9	31.5	6.3	0.33	0.08	4.99	0.89
97/70	5.4	4.38	50.1	22.3	11.9	10.4	27.6	4.6	0.30	0.11	3.55	0.67
00/22	4.8	4.07	71.9	10.0	2.0	7.9	18.1	4.4	0.50	0.13	3.02	0.77
01/016	4.8	6.39	71.3	11.6	4.8	6.8	17.1	3.9	0.33	0.31	1.83	1.40
01/017	4.8	3.86	17.8	52.9	9.8	43.0	29.4	5.5	0.09	0.32	1.82	3.30
MSIRI 398/07	4.6	5.32	38.6	31.2	9.6	21.6	30.2	7.0	0.37	0.24	5.19	1.61
MSIRI 961/08	5.6	6.10	46.2	26.5	14.2	12.4	27.3	14.8	0.05	0.62	9.89	4.18
MSIRI 963/08	4.1	3.51	85.3	4.5	1.1	3.5	10.2	1.8	0.33	0.13	0.86	0.45
MSIRI 1006/08	4.6	3.28	66.5	14.2	1.9	12.3	19.3	2.5	0.47	0.20	1.09	0.76
MSIRI 1007/08	4.4	4.92	49.9	22.8	5.1	17.7	27.3	1.6	0.25	0.26	0.66	0.43
78/60	6.4	5.94	63.3	12.0	3.7	8.3	24.7	22.8	0.85	0.49	16.10	5.31
80/74	5.5	5.67	29.8	33.5	8.5	25.0	36.6	4.9	0.44	0.20	3.05	1.25
80/134	4.6	4.54	67.8	21.1	11.9	9.2	11.1	4.0	0.17	0.22	2.92	0.72
80/310	5.6	4.92	56.1	24.3	15.8	8.5	19.6	7.2	0.49	0.34	4.70	1.63
80/364	7.5	3.89	39.7	30.0	7.4	22.5	30.3	29.0	0.42	0.20	26.19	2.13
Mean value	5.2	4.67	54.0	22.3	7.4	14.9	23.8	7.4	0.37	0.24	5.19	1.61
Standard deviation	0.8	0.91	17.7	11.5	4.5	9.5	7.5	7.4	0.18	0.14	6.42	1.34
Standard error	0.2	0.21	4.2	2.7	1.1	2.2	1.8	1.7	0.04	0.03	1.51	0.32

Soil group and reference code	pH	OM (%)	Particle-size (oven-dried basis)					CEC	K	Na	Ca	Mg
	(H_2O)	Oven-dried basis	Clay (%)	Total sand (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	$cmol^+ kg^{-1}$				
Latosolic Reddish Prairie *(Eutric Cambisol)* *												
97/1	6.5	5.1	39.7	32.8	19.8	13.0	27.4	19.0	0.76	0.37	12.80	5.03
97/2	6.8	4.4	31.6	47.6	25.6	22.1	20.8	18.4	1.22	0.64	10.51	6.00
97/4	6.8	5.0	43.1	36.3	22.3	14.0	20.7	22.7	1.08	0.79	13.47	7.40
97/6	6.4	5.1	52.8	17.2	8.4	8.8	30.0	7.6	0.23	0.30	4.36	2.74
97/7	5.5	4.0	50.9	16.6	7.7	8.8	32.6	7.2	0.23	0.30	4.18	2.52
97/9	5.8	5.2	53.7	20.0	9.2	10.8	26.3	13.3	0.69	0.37	7.77	4.44
97/16	5.0	3.6	65.9	7.1	1.9	5.2	27.0	4.6	0.70	0.19	2.43	1.26
97/34	5.8	4.5	71.2	8.6	3.2	5.4	20.2	12.6	1.37	0.37	6.56	4.29
97/60	7.0	2.8	46.9	36.1	19.5	16.6	17.0	22.0	2.99	0.60	14.37	4.00
97/64	7.3	3.5	48.3	31.8	14.8	17.1	19.9	26.8	3.75	0.49	14.82	7.77
00/24	5.2	6.2	46.5	30.5	11.5	19.0	23.0	8.1	1.18	0.28	3.36	3.24
00/43	5.6	5.1	67.8	12.6	3.0	9.5	19.6	13.3	0.64	0.32	10.26	2.09
00/106	5.8	4.2	49.3	25.5	11.5	14.0	25.3	13.2	1.40	1.10	6.40	4.28
00/107	4.6	6.3	30.3	37.9	11.1	26.8	31.8	3.6	0.23	0.38	1.29	1.64
01/014	5.6	7.5	36.9	34.7	16.7	18.1	28.4	15.2	0.40	0.68	7.79	6.33
MSIRI 773/08	5.5	15.0	32.8	35.9	18.4	17.4	31.3	10.2	1.21	0.52	6.52	1.99
MSIRI 899/08	5.7	4.7	32.7	30.9	12.0	18.9	36.5	6.7	0.28	0.22	5.30	0.88
80/341	6.4	5.1	56.3	24.8	11.2	13.7	18.9	27.8	0.70	0.56	19.70	6.87
Mean value	6.0	5.4	47.6	27.0	12.7	14.4	25.4	14.0	1.06	0.47	8.44	4.04
Standard deviation	0.7	2.6	12.5	11.2	6.7	5.7	5.6	7.4	0.94	0.23	5.00	2.17
Standard error	0.2	0.6	2.9	2.6	1.6	1.3	1.3	1.7	0.22	0.05	1.18	0.51

Soil group and reference code	pH	OM (%)	Particle-size (oven-dried basis)					CEC	K	Na	Ca	Mg
	(H_2O)	Oven-dried basis	Clay (%)	Total sand (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	$cmol^+ kg^{-1}$				
Latosolic Brown Forest *(Dystric / Ferralic Cambisol)* *												
97/12	5.7	6.0	37.3	30.1	14.2	15.9	32.6	6.2	0.23	0.26	3.32	2.37
97/13	5.2	6.4	47.0	23.9	11.5	12.4	29.1	4.0	0.28	0.22	1.84	1.63
97/20	5.0	11.8	39.2	32.0	20.4	11.6	28.8	1.0	0.21	0.19	0.26	0.37
97/24	5.7	6.4	30.4	35.3	16.2	19.1	34.3	4.6	0.35	0.15	3.28	0.81
97/25	5.1	11.6	29.0	45.4	24.6	20.8	25.6	2.3	0.37	0.22	1.10	0.59
97/67	5.9	5.2	31.5	23.2	9.1	14.1	45.3	6.1	0.70	0.11	3.64	1.63
97/68	5.8	6.0	30.1	37.5	16.5	20.9	32.4	5.9	0.35	0.15	3.46	1.93
00/9	5.1	7.5	38.1	35.2	15.8	19.5	26.6	6.4	0.57	0.21	2.59	3.01
00/28	5.4	13.0	26.3	33.9	15.5	18.4	39.8	6.1	0.54	0.31	3.85	1.40
00/38	4.9	4.0	59.5	15.0	2.8	12.2	25.6	6.8	0.18	0.22	3.60	2.80
00/49	5.0	4.8	65.4	14.3	3.7	10.6	20.3	5.1	0.35	0.27	2.75	1.68
00/64	5.4	9.4	25.2	27.9	6.6	21.3	46.9	8.4	0.34	0.44	5.21	2.36
00/65	5.3	6.6	36.9	31.9	9.5	22.5	31.2	6.0	0.37	0.52	2.99	2.10
00/66	5.1	5.4	43.8	31.4	13.2	18.2	24.8	5.3	0.56	0.44	2.33	1.96
00/67	5.0	6.1	42.4	32.7	12.2	20.5	25.0	5.5	0.59	0.32	2.77	1.85
00/70	5.6	7.4	41.6	28.8	11.7	17.1	29.7	6.6	0.58	0.34	3.12	2.58
00/80	5.0	7.6	52.6	23.2	7.6	15.6	24.2	5.5	0.53	0.39	2.50	2.09
00/93	5.3	7.3	34.4	36.8	16.2	20.6	28.9	2.6	0.12	0.37	1.23	0.89
00/111	5.3	12.9	34.6	36.4	18.5	17.9	29.0	7.7	0.69	0.41	3.40	3.23
MSIRI 845/08	4.9	4.7	42.6	15.0	4.6	10.4	42.4	4.1	0.46	0.21	2.64	0.78
MSIRI 848/08	5.3	6.2	32.6	33.9	9.5	24.5	33.5	5.5	0.91	0.43	1.08	3.12

Soil group and reference code	pH	OM (%)	Particle-size (oven-dried basis)					CEC	K	Na	Ca	Mg
	(H_2O)	Oven-dried basis	Clay (%)	Total sand (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	$cmol^+ kg^{-1}$				
Latosolic Brown Forest *(Dystric / Ferralic Cambisol)* *												
MSIRI 850/08	4.8	7.3	40.4	33.2	12.3	20.9	26.4	2.9	0.42	0.36	1.28	0.84
MSIRI 868/08	7.2	5.5	34.3	39.4	21.1	18.4	26.2	5.7	1.05	0.28	2.86	1.47
MSIRI 900/08	5.0	5.8	34.1	25.8	9.6	16.2	40.1	4.4	0.27	0.35	2.19	1.57
MSIRI 902/08	5.2	8.0	30.0	38.6	19.4	19.2	31.4	5.6	0.48	0.55	2.16	2.45
MSIRI 904/08	4.5	4.3	70.6	11.5	4.7	6.8	17.9	4.2	0.78	0.22	2.33	0.84
MSIRI 988/08	4.4	5.1	53.9	27.3	4.9	22.4	18.9	1.5	0.18	0.21	0.57	0.55
79/92	5.3	5.0	26.9	39.9	25.5	14.4	33.3	2.2	0.11	0.11	1.31	0.70
Mean value	5.3	7.0	39.7	30.0	12.8	17.2	30.4	4.9	0.45	0.30	2.49	1.70
Standard deviation	0.5	2.5	11.6	8.5	6.2	4.3	7.3	1.8	0.23	0.12	1.11	0.84
Standard error	0.1	0.5	2.2	1.6	1.2	0.8	1.4	0.3	0.04	0.02	0.21	0.16

APPENDIX 2: Degree of phosphorus saturation (DPS_{ox}), 0.1M H_2SO_4-P and 0.01M $CaCl_2$-P in soils selected for the study on the 'Evaluation of the P status of sugarcane soils in Mauritius using agronomic and environmental criteria'.

Soil group and reference code	**P_{ox}**	**Fe_{ox}**	**Al_{ox}**	**DPS_{ox}**	**0.1M H_2SO_4-P**	**0.01M $CaCl_2$-P**
	(mmol kg^{-1})			(%)	(mg kg^{-1})	(µg L^{-1})
Low Humic Latosol *(Humic Nitosol)* *						
97/41	5.1	88	145	2.19	57	21.7
97/42	6.5	94	153	2.65	40	25.6
97/47	3.7	88	171	1.43	34	12.3
97/48	5.6	90	160	2.22	70	19.2
97/49	2.1	65	139	1.05	21	22.4
97/53	11.6	263	265	2.20	121	25.7
97/58	15.3	164	145	4.95	197	48.2
97/59	7.6	135	118	2.99	81	31.4
97/61	13.7	116	204	4.28	151	46.6
97/73	2.9	65	94	1.84	40	20.5
00/4	2.3	59	151	1.11	13	9.2
00/5	6.2	217	520	0.84	45	36.0
00/34	14.2	138	810	1.50	177	39.3
00/59	7.7	127	124	3.10	68	12.4
00/60	6.6	138	90	2.91	43	15.2
00/76	4.7	120	146	1.76	70	39.6
00/77	11.3	129	153	4.02	82	20.1
00/84	9.3	117	171	3.21	80	10.8
00/100	4.9	78	103	2.71	33	16.8
00/108	5.3	178	108	1.86	34	22.4
00/115	4.2	104	99	2.05	48	18.3
MSIRI 853/08	9.2	81	146	4.04	131	34.1
MSIRI 855/08	11.0	143	122	4.15	104	29.8
80/12	6.8	63	175	2.86	210	31.9
80/76	11.8	99	158	4.60	160	27.9
80/85	13.6	136	123	5.24	157	43.1
80/119	4.0	263	130	1.58	24	49.5
Mean value	7.7	124	182	2.72	85	27.0
Standard deviation	3.9	55	149	1.25	58	11.8
Standard error	0.8	11	29	0.24	11	2.3

*Soil group as per FAO classification (Arlidge and Wong You Cheong, 1975).

Soil group and reference code	P_{ox}	Fe_{ox}	Al_{ox}	DPS_{ox}	$0.1MH_2SO_4$-P	0.01M $CaCl_2$-P
	(mmol kg^{-1})			(%)	(mg kg^{-1})	(µg L^{-1})
Humic Latosol *(Humic Nitosol)* *						
97/18	25.1	153	289	5.69	196	26.9
97/45	7.6	79	123	3.75	63	13.2
97/46	4.5	98	179	1.63	48	14.7
97/52	7.5	133	186	2.35	109	16.1
97/70	4.5	60	136	2.31	60	7.2
00/22	9.0	92	578	1.34	76	19.2
01/016	4.8	129	128	1.87	50	10.8
01/017	2.3	164	111	0.82	19	9.7
MSIRI 398/07	15.2	114	191	4.99	171	22.6
MSIRI 961/08	18.2	550	414	1.89	115	54.9
MSIRI 963/08	10.1	91	115	4.87	106	29.4
MSIRI 1006/08	1.6	52	91	1.12	25	22.6
MSIRI 1007/08	11.6	87	501	1.97	127	22.6
78/60	11.6	254	391	1.79	293	43.4
80/74	7.8	169	301	1.66	60	22.6
80/134	12.4	88	168	4.83	104	16.6
80/310	11.4	122	196	3.58	84	18.4
80/364	10.0	65	115	5.54	150	36.5
Mean value	9.7	139	234	2.89	103	22.6
Standard deviation	5.8	114	146	1.64	68	13.5
Standard error	1.4	27	34	0.39	16	3.2

Soil group and reference code	P_{ox}	Fe_{ox}	Al_{ox}	DPS_{ox}	$0.1MH_2SO_4$-P	0.01M $CaCl_2$-P
	(mmol kg^{-1})			(%)	(mg kg^{-1})	(µg L^{-1})
Humic Ferruginous Latosol *(Humic Acrisol)*						
97/19	4.5	113	86	2.24	25	14.8
97/26	7.8	143	175	2.44	74	8.7
97/66	5.9	124	144	2.21	48	9.0
97/72	7.0	121	153	2.57	79	10.8
00/72	1.7	186	144	0.52	13	5.8
00/73	4.3	642	192	0.51	26	8.6
00/74	3.4	116	75	1.76	44	5.9
00/81	6.5	239	157	1.64	47	8.8
00/95	5.0	150	141	1.70	35	11.0
00/96	7.4	178	245	1.75	65	10.4

Soil group and reference code	P_{ox}	Fe_{ox}	Al_{ox}	DPS_{ox}	$0.1MH_2SO_4$-P	0.01M $CaCl_2$-P
	(mmol kg^{-1})			(%)	(mg kg^{-1})	(µg L^{-1})
Humic Ferruginous Latosol *(Humic Acrisol)*						
00/97	5.3	138	138	1.92	118	9.5
00/99	6.1	180	152	1.84	39	9.5
00/118	6.6	59	71	5.07	87	16.9
00/119	6.0	55	83	4.37	101	17.4
00/120	6.1	82	64	4.17	68	10.4
MSIRI 860/08	5.3	195	135	1.61	34	10.4
MSIRI 901/08	8.1	113	132	3.29	68	10.0
MSIRI 959/08	15.9	220	232	3.52	65	10.4
80/32	9.2	123	151	3.34	121	31.0
80/98	19.8	350	558	2.18	140	19.3
ACIAR 1	13.1	149	126	4.76	94	16.8
Mean value	7.4	175	160	2.54	66	12.2
Standard deviation	4.2	126	103	1.28	34	5.7
Standard error	0.9	27	22	0.28	8	1.2

Soil group and reference code	P_{ox}	Fe_{ox}	Al_{ox}	DPS_{ox}	$0.1MH_2SO_4$-P	0.01M $CaCl_2$-P
	(mmol kg^{-1})			(%)	(mg kg^{-1})	(µg L^{-1})
Latosolic Brown Forest *(Dystric/Ferralic ambisol)*						
97/12	13.7	357	621	1.40	75	19.9
97/13	9.4	365	450	1.15	65	24.2
97/20	27.2	646	1450	1.30	127	14.6
97/24	14.0	310	524	1.68	116	13.4
97/25	28.5	618	872	1.91	219	16.1
97/67	7.6	192	372	1.35	46	18.0
97/68	13.7	382	642	1.34	103	18.0
00/9	19.4	435	632	1.82	148	18.9
00/28	25.0	352	1170	1.64	244	15.8
00/38	7.6	264	217	1.58	32	9.7
00/49	7.1	137	193	2.14	40	13.6
00/64	21.0	525	709	1.70	116	14.8
00/65	9.0	88	484	1.57	36	19.6
00/66	12.0	294	497	1.52	84	15.4
00/67	25.4	379	481	2.95	210	20.4
00/70	15.7	320	560	1.78	129	22.2
00/80	15.7	343	416	2.06	105	22.4

Soil group and reference code	P_{ox}	Fe_{ox}	Al_{ox}	DPS_{ox}	0.1M H_2SO_4-P	0.01M $CaCl_2$-P
	(mmol kg^{-1})			(%)	(mg kg^{-1})	(µg L^{-1})
Latosolic Brown Forest *(Dystric / Ferralic Cambisol)*						
00/93	14.8	324	803	1.31	106	10.5
00/111	26.5	491	636	2.35	217	22.7
MSIRI 845/08	7.8	78	148	3.45	74	15.6
MSIRI 848/08	9.7	418	*513*	1.04	79	41.0
MSIRI 850/08	17.4	489	641	1.54	158	44.4
MSIRI 868/08	16.7	389	256	2.59	144	16.1
MSIRI 900/08	14.1	465	422	1.59	81	40.8
MSIRI 902/08	19.7	540	320	2.28	160	41.2
MSIRI 904/08	11.0	133	198	3.33	105	21.8
MSIRI 988/08	7.0	189	121	2.25	51	23.0
79/92	2.9	198	118	0.90	22	9.1
Mean value	14.1	322	417	2.02	106	23.0
Standard deviation	6.5	154	212	0.73	56	11.2
Standard error	0.3	8	11	0.04	3	0.6

Soil group and reference code	P_{ox}	Fe_{ox}	Al_{ox}	DPS_{ox}	0.1M H_2SO_4-P	0.01M $CaCl_2$-P
	(mmol kg^{-1})			(%)	(mg kg^{-1})	(µg L^{-1})
Latosolic Reddish Prairie *(Eutric Cambisol)*						
97/1	14.3	235	218	3.16	138	33.5
97/2	25.8	697	386	2.38	177	31.4
97/4	19.1	528	290	2.33	81	29.6
97/6	17.6	480	445	1.90	94	29.3
97/7	12.5	308	207	2.43	57	27.2
97/9	13.3	355	252	2.19	69	29.6
97/16	6.8	128	207	2.03	63	25.7
97/34	6.6	186	180	1.79	37	33.8
97/60	15.3	360	376	2.45	110	40.1
97/64	17.8	431	276	2.51	171	64.6
00/24	10.2	352	322	1.51	82	27.5
00/43	18.1	182	134	5.71	177	36.2
00/106	8.7	397	443	1.03	35	25.9
00/107	7.7	289	481	1.00	49	14.2
01/014	13.9	579	765	1.03	60	17.9

Soil group and reference code	P_{ox}	Fe_{ox}	Al_{ox}	DPS_{ox}	0.1M H_2SO_4-P	0.01M $CaCl_2$-P
	(mmol kg^{-1})			(%)	(mg kg^{-1})	(µg L^{-1})
Latosolic Reddish Prairie *(Eutric Cambisol)*						
97/1	14.3	235	218	3.16	138	33.5
97/2	25.8	697	386	2.38	177	31.4
97/4	19.1	528	290	2.33	81	29.6
97/6	17.6	480	445	1.90	94	29.3
97/7	12.5	308	207	2.43	57	27.2
MSIRI 773/08	32.1	488	1297	1.80	157	26.0
MSIRI 899/08	10.9	78	111	5.73	170	25.6
80/341	24.5	412	376	3.11	137	37.3
Mean value	15.3	360	376	2.45	104	30.9
Standard deviation	6.9	162	277	1.35	52	10.5
Standard error	1.6	38	65	0.32	12	2.5