CHANGES IN THE PHOSPHORUS STATUS OF SOILS AND THE INFLUENCE ON MAIZE YIELD

by

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A thesis submitted in accordance with the requirements for the Philosophiae Doctor degree in the Department of Soil, Crop and Climate Sciences, Faculty of Natural and Agricultural Sciences at the University of the Free State, Bloemfontein

May 2003

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ABSTRACT

The principle objective of this study was to obtain P fertilizer guidelines for large maize producing areas west of the Drakensberg mountains according to a similar approach previously used in KwaZulu-Natal based on the sufficiency concept of soil extractable P.

Data from 14 different P fertilizer trials at various localities in the Free State, Gauteng, Mpumalanga and North West provinces was used. Different phosphorus treatments were applied for all trials in order to establish differences in extractable soil P levels which were expected to have corresponding effects on maize yield. Long-term rainfall varied from 990 mm per annum for the Athole trial in the eastern maize producing region to 494 mm per annum for the Wolmaransstad trial in the western region. The duration of trials varied between one and nine seasons.

Firstly, simple regression equations with high R^2-values were obtained for relationships between Ambic 1 and Bray 1 extractions over soils, but since it was demonstrated that relationships for different soils differed significantly from each other the use of these equations may result in a very high degree of inaccuracy with respect to P fertilizer recommendations. Soil properties had a significant effect on the efficacy of the two extractants. Furthermore, slopes of relationships between Ambic 1 and Bray 1 could be predicted by using exchangeable Ca in simple regression relationships (R^2-values of between 80 and 83 %).

Secondly, it was established that P requirement factors (PRF's) cannot be obtained over soils (R^2-values varied between 10 and 54 %), but rather for different soils separately (R^2-values varied between 75 and 99 %). Differences between the PRF's in total soil volumes (1.7 to 63.2 for Ambic 1 concentrations and 0.8 to 27.3 for Bray 1 quantities) indicated that the soils used in this study differed in their behavior to applied P. Phosphorus requirement factors could be predicted by a simple regression equation using degree of leaching based on the clay content as input parameter (R^2-values between 60 and 78 %) as well as six multiple regression equations using either one of exchangeable Ca, Mg, K, silt content or degree of leaching based on the clay content (R^2-values between 52 and 99 %) as input parameters. The implementation of any of these regression equations should be practical since all the parameters are usually included in standard analysis. However, the simple regression with degree of leaching based on the clay content appears to be an obvious option above the multiple regression equations since it is based on five input variables, i.e. exchangeable Ca, K, Mg, Na and clay content.

Lastly, threshold extractable P values were derived for 10 out of the 14 localities that have been included in this study with varying R^2-values. These threshold extractable P values were related to soil properties and it was found that the degree of leaching and silt-plus-clay content were the parameters that explained most of the variation. However, it was decided to explore only the relationships between threshold extractable P values and silt-plus-clay contents in more detail. By excluding data from two localities of which the topsoil contained lime, the R^2-values of the mentioned relationships improved substantially so that threshold extractable P values could be derived from the silt-plus-clay content range of the other eight localities. For example the threshold extractable soil P concentrations based on Bray 1 for the total soil volume to obtain 90 % relative yield varied from 33.5 mg kg^{-1} at 13 % silt-plus-clay to 14.6 mg kg^{-1} at 60 % silt-plus-clay. These P (Bray 1) thresholds are much higher on the sandy soils than the value of 19 mg P kg^{-1} (Bray 1) for 95 % relative yield currently in use according to existing guidelines. This may not necessarily imply that more P fertilizers will be sold according to higher soil P thresholds obtained in this study, since the corresponding soil sampling procedure also measures more residual P from enriched zones over rows where P fertilizer was band placed. The soil sampling procedure according to existing guidelines excludes sampling from these zones.

Key words : Ambic 1, Bray 1, extractable P, P fertilizer guidelines, P requirement factors, relationships, soil P thresholds, soil properties

DECLARATION

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

C.J.J. SCHMIDT

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ACKNOWLEDGEMENTS

I hereby express my sincere gratitude towards those who contributed in the shaping of my life as set by our Creator, Elohim :

- my parents for sending me off to university, keeping me there and supporting me,
- my wife for her support,
- my mentors : - the late Prof. R. du T. Burger, Prof. A.T.P. Bennie, Prof. C.C. du Preez, Dr. P.A.L. le Roux, Dr. A. Singels and Dr. M. Hensley,
- my supervisors : - Prof. C.C. Du Preez and Dr. F.G. Adriaanse,
- statistical support : - Ms. M. Smith and Ms. L. Morey (ARC-Biometry Division) for ANOVA's and regressions,
- and the ARC for financial support and allowing me the use of research data for this study.

CHAPTER 1

INTRODUCTION

The element P differs from C, N and S, since it does not have a significant gaseous atmospheric transfer, however, it has significant indirect global effects on the environment through its effects on C, N and S transfers (Stewart, 1990). Phoshorus is a key element, a biological necessity by playing a major role in the existence of all living creatures (Anon, s.a.; McWilliam, 1976; Stewart, 1990) and is required by all living organisms and every living cell (Jones, 1982). Among other things P ensures the transfer and storage of energy (Stewart, 1990) and permits the conservation and transmission of genetic characteristics in plants as well as in man and animals (Anon, s.a.). Thus, living creatures have an absolute need for P, and it is mainly agriculture which provides man and animals with this indispensable element (Anon, s.a.; McWilliam, 1976).

A major limitation to plant growth in most agricultural soils is an inadequate supply of essential cations and anions, with P supply being among the most crucial. Although the total P pool in soils is usually large (Larsen, 1976; Smith, 1976), P occurs in highly insoluble forms as organic complexes, crystals, salts, or attached to the base exchange complex (Smith, 1976), consequently only a small part is at the disposal of the crop (Larsen, 1976). Their high degree of insolubility prevents loss by leaching, but has the major disadvantage that plants cannot always obtain a satisfactory supply from the equilibrium solution in soil (Smith, 1976). According to a analysis, based on 6900 trials, P accounted for 35 % of the total yield increase brought about by N, P and K application (Goswami, Kamath & Santoso, 1990). Estimates of the contribution that fertilizer makes to increased food production range as high as 50 to 75 % in developing countries, 30 to 40 % in the USA and 20 to 25 % worldwide (Harre & White, 1985). However, soil fertility decline is occurring over large parts of the world, particularly the developing world (Ayoub, 1999) where the loss of soil fertility from continual nutrient mining by crop removal without adequate replenishment (FAO, 1998; Ayoub, 1999), combined with imbalanced plant nutrition practices, poses a serious threat to agricultural production. It is already causing yield decreases as large as those caused by other forms of environmental degradation (FAO, 1998).

Soil fertility is a dynamic concept influenced by climate and cultural practices (Munson, 1982; Ayoub, 1999). The use of mineral fertilizers, however is essential for achieving stable and increasing food production worldwide (Grunes & Allaway, 1985; Stewart, 1990; FAO, 1998), but as they have an impact on the soil, water, air, plant and human health (FAO, 1998), the efficient use of fertilizers is crucial. As mineral fertilizers also increase root growth, they improve soil structure and in turn reduce soil loss through erosion. The increased biomass production also results in greater carbon sequestration and hence contributes to reduction of CO_2. Crop specific fertilization produces balanced nutrition and high quality food (Ayoub, 1999). The inefficient use not only increases negative environmental impact (Stewart, 1990) unnecessarily, but also represents a large waste of natural resources and a substantial economic loss (FAO, 1998). For example, P associated with eroded sediments from agricultural lands and P discharges from urban and industrial areas as sewage effluents and other wastes are major causes of eutrophication of water bodies (Stewart, 1990). To improve the efficiency of fertilizer use is a major challenge. There is also scope for improved products, but the greatest medium-term gain could be had from improving the way in which currently available fertilizers are used. Most of the adverse effects of fertilizer use results from inadequate knowledge among farmers. Farmers must know how to use fertilizers efficiently under their own particular circumstances (FAO, 1998).

It is estimated that, by the year 2020 at a global level, 70 % of plant nutrients will have to come from fertilizers. Fertilizers are thus indispensable for sustained food production (Grunes & Allaway, 1985), but excessive use of mineral fertilizers has roused environmental concerns (Ayoub, 1999). According to Stangel & Von Uexkull (1990) food production can be increased by increases in the area under crops, increases in cropping intensity and increases in yields. Fertilizers also enable both the potential of modern seed varieties to be tapped and substantial progress to be made with established cropping systems (Maene, 1990).

Two significant factors that led to developments in the fertilizer industry were improvements in the manufacture of fertilizers that permitted more economical production of higher analysis fertilizers and a sharp expansion in fertilizer use enhanced by research, extension and industry educational efforts to show the value of fertilizers to farmers, along with increased worldwide demand for more food production (Young, Westfall & Colliver, 1985). Fertilizer inputs in agricultural production systems have generally been regarded as variable inputs, incurring a recurrent cost. However, for phosphate fertilizers in particular, residual effects occur for a number of years following fertilizer application. Many agronomists have recognised this and realised all the returns from a phosphate application are not received in the year of application (Helyar & Godden, 1976). With continued application of fertilizers containing only those nutrients to which the plants respond, and removal of abundant harvests, these naturally occurring reserves can be depleted. If the reserves of an element required by plants become depleted, evidence of plant deficiencies of this element should lead to its inclusion in the fertilizer to maintain crop yields at the desired level (Grunes & Allaway, 1985).

Although on a global scale there is no shortage of phosphate rock for use in industry and fertilizers, reserves of high quality ores are being rapidly depleted. This will result in a need for new technology to utilize lower grade ores with high contents of silica and sesquioxides. High costs of production of soluble fertilizer products, together with indications of lower residual value, have stimulated the development of alternative approaches (Harre & White, 1985; Stewart, 1990), including more direct application to the rhizosphere of crops or the use of reactive phosphate rock and partially acidulated products. There is also an urgent need to develop improved methods for recycling of P in wastes, particularly human and animal wastes. For example, recent studies on P transformations focus on microbial activity and the importance of both inorganic and organic forms, as organic P forms are both a significant source and sink for biologically active P in ecosystems (Stewart, 1990).

According to the population projections of the World Bank, the world's population will increase from 6 billion people in 1999 to 7 billion in 2020. The FAO estimates that during the period 1995 to 1997 about 790 million people in the developing world did not have enough to eat. This number has been falling in the recent past at an average of around 8 million people per annum. The issue of introducing agricultural systems and improved technologies is particularly important for farmers, commercial and small-scale, since improved productivity provides not only more food, but also increases income (FAO, 2000).

Considering the importance of plant nutrients to agricultural production, it is imperative to establish relationships between yield, use of plant nutrients, economic feasibility and environmental quality. What farmers need to know is which plant nutrients and how much they should apply to provide the optimum economic increase in yield without damaging the environment. The answer depends on the ecological, social and economic characteristics of each farming system (FAO, 1998). As food supply and soil productivity are directly related to soil fertility, fertilizer use and plant nutrition (Munson, 1982), raising the efficiency of crop production by improving plant and fertilizer management is arguably the best way of protecting natural resources such as land and fossil energy reserves, while contributing to the food supplies needed by a growing planetary population (Ayoub, 1999). Soil fertility is a general term directly related to the ability of the soil to supply the elements essential for crop growth, development and maturation for high yields. The degree of soil fertility is related to the capacity of soils to supply the essential elements at the rates and in the amounts required to produce high-yielding, high-quality crops on a sustained basis (Stewart, 1990). As scientific information is increasingly needed to guide the use of P to obtain maximum benefits without producing undesirable impacts on the environment (Stewart, 1990), man's objective in studying soil fertility is to determine action that can be taken to improve the nutrient availability and make soils more productive (Munson, 1982).

Therefore, overall objectives with this study were to review P in the soil-plant system concisely (Chapter 2), and to establish relationships (a) between Ambic 1 and Bray 1 extractable soil P (Chapter 4), (b) between extractable soil P and fertilizer P application (Chapter 5) and (c) between maize yield and extractable soil P (Chapter 6), with the ultimate objective to improve existing P fertilizer guidelines for maize production (Chapter 7).

CHAPTER 2

LITERATURE ON PHOSPHORUS IN THE SOIL-PLANT SYSTEM

2.1 Introduction

Phosphorus is an essential nutrient for plant growth and due to its low concentration and solubility in soils, can be regarded as a critical nutrient, often limiting plant growth. In natural ecosystems, P availability is controlled by sorption, desorption and precipitation of P released during weathering and dissolution of rocks and minerals of low solubility. Phosphorus availability is thus generally inadequate for crop needs in production agriculture and can be defined as that P in soil or water that is available by desorption and dissolution processes for uptake by plants in terrestrial and aquatic ecosystems. Furthermore, complex and interrelated processes determine the amounts and availability of several inorganic and organic forms of soil P (Sharpley, 2000).

This literature review will be restricted to P in the soil-plant system. Aspects about phosphorus that will be covered are the cycle, gains and losses in soils, transformations by biological and physico-chemical processes in soils, uptake and function in plants, effects of deficiency in plants, sources to plants, movement from soil to plants, movement and translocation within plants and finally, recommendations for crops.

2.2 The phosphorus cycle

Various P cycles were suggested in literature (Katchman, 1961; Epstein, 1972; Sharpley & Rekolainen, 1997; Brady & Weil, 1999), but for the purpose of this study, the cycle suggested by Havlin, Beaton, Tisdale & Nelson (1999) is presented in Figure 2.1. This cycle will be used to describe the interrelationships of the various forms and processes of P within soils.

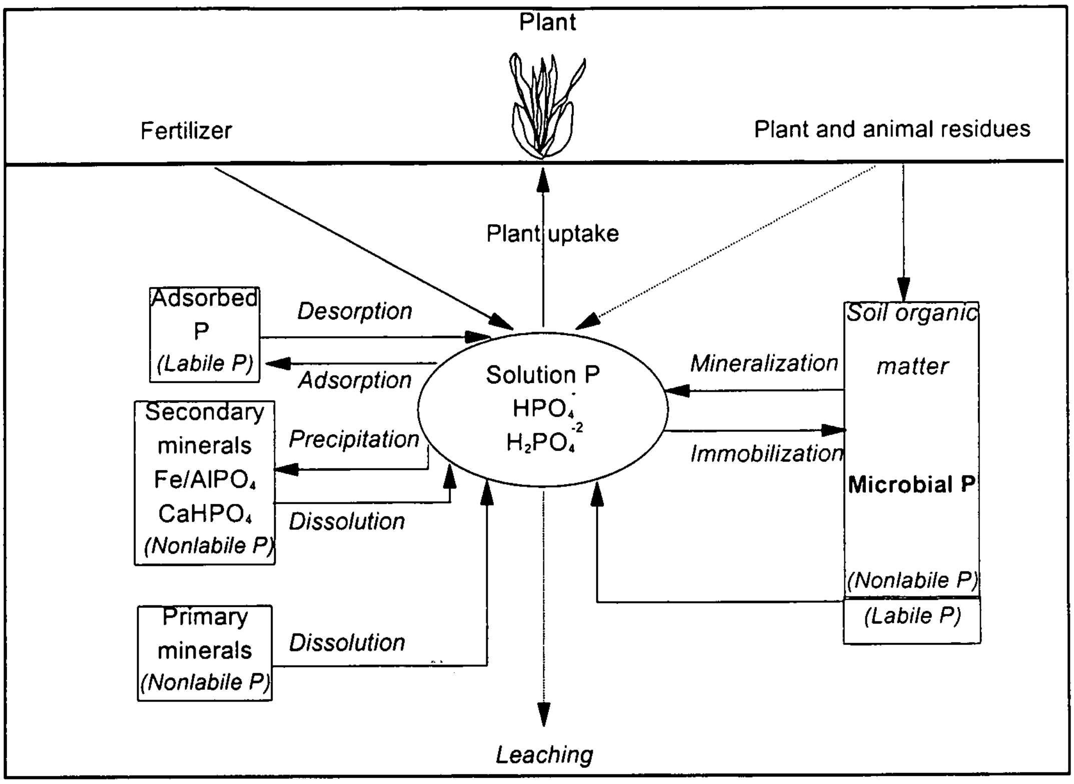


Figure 2.1 : Phosphorus cycle to describe the interrelationships of the various forms and processes of P within soils (Havlin et al., 1999).

Unlike C and N, the lithosphere is the source and reservoir of P with an approximate P content of 0.12 %. Phosphorus enters into the biosphere by being absorbed by plants and micro-organisms. Upon decomposition of plants and their animal consumers, soluble P returns to the soil. Although release of P from insoluble forms in rocks and soils is slow, the sum total of P carried by the rivers into the oceans each year is enormous. Estimates are that 3.5 million tons of P are lost to the sea annually, where it precipitates in the form of sparingly soluble calcium phosphate. Only a small part of this P returns to the land, through guano deposited by sea birds, and by man taking fish from the oceans (Mellor, 1928; Van Wazer, 1961; Epstein, 1972; Jones, 1982). However, elemental P is never found on the earth, as all P is in the form of phosphates either as water soluble or insoluble inorganic orthophosphates, found in freshwater lakes, seas, as well as in the soil (Mellor, 1928; Katchman, 1961). In soils the total P comprises soil solution P, inorganic P and organic P (Havlin et al., 1999).

Total P

Although P sediments are widely distributed in the lithosphere of the earth (Johnston, 2000), P does not occur as abundantly in soils as N and K (Havlin et al., 1999) and is next to N the most deficient element for plant growth in the cultivated soils of the world (Jones, 1982). In comparison with other essential major nutrients, the total P content of the earth's crust is low, i.e. 1100 to 1200 mg kg^{-1} according to Morgan (1997), but 0.005 to 0.15 % according to Jones (1982) and Havlin et al. (1999). The total P content of a soil generally decreases with depth down the profile, with relatively small amounts being found below 400 to 500 mm, varying with parent material and consequently soil type, influenced by indirect parameters such as texture and organic C content (Harrison, 1987). However, large proportions of the total P content of soils may exist in forms that are difficult to utilize, therefore total P is poorly correlated with plant available P and is rarely used to describe the P fertility status of soils (Jones, 1982; De Datta, Biswas & Charoenchamratcheep,1990; Havlin et al., 1999).

Soil solution P

The median concentration of P in the soil solution is approximately 0.05 mg kg^{-1} (Anon, s.a.; Havlin et al., 1999), seldom reaches levels higher than 0.03 mg kg^{-1} in soils not having a history of fertilization (Young et al., 1985) and is subjected to rapid changes (Blair, Till & Smith, 1976). However, conflicting reports exist in literature about the availability of organic P in soil solution (Dalal, 1976). The amount of phosphate ions present in the soil solution, i.e. $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-}, depends on soil solution pH (Young et al., 1985; Havlin et al., 1999), but all are likely to be present at the pH values likely to be found in most soils (Addiscott & Thomas, 2000). Ultimately, the P concentration in solution is controlled by the solubility of inorganic P minerals in soil (Anon, s.a.; Havlin et al., 1999).

Inorganic P

In most soils there is a substantial reserve of inorganic P, which may be present in one or more of a number of different forms that may vary considerably in availability (Norman, 1953) or solubility, of which the most common in the earth's crust is apatite (Anon, s.a.; Peck, 1971; Addiscott & Thomas, 2000), particularly in soils with a pH more than 7, i.e. calcareous soils. According to different reports, soil inorganic P represents approximately 20 to 80 %, 50 to 75 %, or 10 to 90 % of the total P (Anon, s.a.; Morgan, 1997; Sharpley & Rekolainen, 1997) and can be classified into four groups, i.e. iron phosphate (Fe-P), aluminium phosphate (Al-P), calcium phosphate (Ca-P) and occluded Fe-P and Al-P. Phosphorus in all forms exists in all soils, but Al-P and Fe-P are more abundant in acid soils (Anon, s.a.), while Ca-P dominates in neutral to alkaline soils (Jones, 1982; Shapiro & Fried, 1985; Mengel & Kirby, 1987; De Datta et al., 1990; Havlin et al., 1999). During a study on 9 different soil types of central South Africa at 50 different localities with clay contents ranging from 4 to 57 %, it was found that the inorganic P of cultivated areas ranged between 33 and 249 mg kg^{-1}, while that of adjacent grasslands ranged between 21 and 197 mg kg^{-1} (Van Zyl, 1995).

Organic P

The organic fraction involves the microbiological mineralization of organic to inorganic P (Shapiro & Fried, 1985) and is therefore considered a valuable source of available P (Anon, s.a.; Shapiro & Fried, 1985; Martin, Celi & Barberis, 1999; Williams, Shand, Sellers & Young, 1999). In most soils the organic P varies between 15 and 80 % of total P (Blair et al., 1976; Hedley, Stewart & Chauhan, 1982; Mengel & Kirby, 1987; Havlin et al., 1999; Schnitzer, 2000), but only less than one-half of this has been identified so far (Dalal, 1976; Schnitzer, 2000). Organic P is often fractionated using chemical extractions, giving fractions that are defined in terms of the extractant (Hedley et al., 1982). Methods for the fractionation of soil P were described, experimented and reported by various researchers, i.e. Hedley et al. (1982), Lindo, Taylor, Adriano & Shuford (1995), Van Zyl (1995), Du Preez & Claassens (1999), Maroko, Buresh & Smithson (1999), Sui, Thompson & Shang (1999), Thomas, Johnson, Frizano, Vann, Zarin & Joshi (1999), Daroub, Pierce & Ellis (2000) and Johnston (2000). During a study on nine different soil types of central South Africa at 50 different localities with clay contents ranging from 4 to 57 %, it was found that the organic P content of cultivated areas with cultivation periods ranging from 5 to 90 years, ranged between 67 and 482 mg kg^{-1} while that of adjacent grasslands ranged from 54 to 311 mg kg^{-1} (Van Zyl, 1995). Though there are reports that organic P can be taken up directly by plants, it is considered that only a small proportion is obtained in this way (Harrison, 1987). Although many of the organic P compounds in soils have not been characterized (Havlin et al., 1999), fractions that have been identified in soils and soil extracts can be categorized (Schnitzer, 2000). The approximate relative labile proportion of these compounds in total organic P is 10 to 50 % inositol phosphates, 1 to 5 % phospholipids and 0.2 to 2.5 % nucleic acids (Dalal, 1976; Hedley et al., 1982; Sharpley & Rekolainen, 1997), while more resistant forms are comprised of humic acids. Thus, on average, only about 50 % of organic P compounds in soils are known (Morgan, 1997; Havlin et al., 1999; Addiscott & Thomas, 2000).

2.3 Phosphorus in soils

As illustrated in Figure 2.1, various processes are determining the level of plant available P in a soil, i.e. uptake by plants, mobilization of native and residual P upon depletion of the pool of available P (labile reserve), immobilization of available P by retention (non-labile reserve) after enrichment of the available pool by fertilizers and residues, and losses through leaching and erosion. Thus, the reaction rates which should be considered with regard to the quantity of available P in a soil are not only the rates of mobilization and immobilization, but also the rate by which P in fertilizers and residues enters the labile pool, the rate at which plants absorb P from the labile pool, as well as the rate of P loss by leaching and erosion from the labile pool. Under conditions of equilibrium the reaction rates of mobilization and immobilization between labile and non-labile P in soil will be equal (Larsen, 1976; Ross, 1989). For the P cycle to be in equilibrium, it is not that simple (Helyar & Godden, 1976) as the inorganic and organic chemistry of P compounds in soil is of great complexity (Norman, 1953).

2.3.1 Phosphorus gains and losses

2.3.1.1 Gains

In this section the focus will be on gains through fertilizers, since gains through residues will be covered elsewhere. Phosphorus fertilizers are used to supplement the natural soil nutrient supply in order to satisfy the demand of crops with a high yield potential and produce economically viable yields, to compensate for the nutrients lost by the removal of plant products, leaching or gaseous loss. The existence of a close relationship between fertilizer consumption levels and agricultural productivity has been established beyond doubt (Terman, 1982; Grunes & Allaway, 1985; De Larderel & Maene, 1998; Härdter & Krauss, 1999; Johnston, 2000). The chemical characteristics of the soil and the P fertilizer source determine soil-fertilizer reactions, which influence fertilizer availability to plants (Havlin et al., 1999). Applied P fertilizers, after dissolution in the soil water, are quickly immobilized by reactions with various soil constituents and are therefore not relatively accessible to crop roots. As a result, P nutrition of field crops is largely dependant on the subsequent release of P from these reaction products to the soil water (Morgan, 1997). The effectiveness of a P fertilizer for a particular crop depends on its capacity to provide the crop with P over and above that which the plant can get from the unfertilized soil and at a rate to meet the crop's requirement for optimum growth (Barrow, 1990; Chien, Sale & Hammond, 1990; Goswami et al., 1990; Hedley, Hussin & Bolan, 1990). However, various factors and principles should be considered in order to optimize P fertilization. Various sources can be used for the amendment of P in the soil.

Organic P

Animal and municipal wastes are excellent sources of plant available P. The form and content of P in fresh animal waste varies greatly depending on the P content of the feed and the type of animal. For South African conditions, the P content of guano, raw cattle manure and chicken manure are approximately 4.8, 0.4 and 1.5 %, respectively. Composted cattle manure and dried sewage contains roughly 0.8 and 1.5 % P, respectively (MVSA, 1997). Organic P compounds can move to a greater depth than inorganic P in soil solution. Thus, continued application of manure can result in elevated P levels at 540 to 1080 mm depths. In contrast, application of the same quantity of P as inorganic fertilizer P results in much less downward movement of P (Havlin et al., 1999).

Inorganic P

Mineral fertilizers are materials, either natural or manufactured, containing plant nutrients essential for the normal growth and development of plants, where plant nutrients are food for plants some of which are used directly for human food, others to feed animals, supply natural fibres or produce timber (De Larderel & Maene, 1998). Terms used to describe the P content in fertilizers are water-soluble, citrate-soluble, citrate-insoluble, available and total P. A small fraction that is extractable with water, is known as water-soluble P. The remaining water-insoluble P that is extractable with 1 *N* ammonium citrate is known as citrate-soluble P. The sum of the water- and citrate-soluble P represents plant available P. The remaining P in the sample is known as citrate-insoluble P, while the sum of available P and citrate-insoluble P represents the total amount of P present in the soil (Jones, 1982; Chien et al., 1990; Havlin et al., 1999). With some adjustments and good management, phosphate rock (PR) can be used as P fertilizer for crop production (Rajan, Watkinson & Sinclair, 1996), but mainly on acid soil, as the solubility is low, i.e. only 5 to 17 % citrate-soluble P (Terman, 1982; Simpson, 1991; MVSA, 1997).

Microbial P

The use of micro-organisms to increase plant available P has been documented. Since the 1950's, bacteria collectively called *Phosphobacteria* have been soil applied to increase the P uptake and yield of crops. Although an average of 10 % yield increases has been reported, results varied. In the 1980's several fungi, in particular *Penicillium bilaii*, were shown to increase P uptake, especially on high-pH, calcareous soils. Increased solubilization of native soil mineral P and added PR have been observed (Havlin et al., 1999).

2.3.1.2 Losses

In this section attention will be given to losses other than through crop removal, since these processes have an impact on the environment. The effect of injudicious P fertilizer use on the environment is a major concern (Lennox, Foy, Smith & Jordan, 1997) and focusses primarily on accelerated eutrophication of surface waters (Stewart, 1990). Eutrophication, the rapid growth and decay of aquatic vegetation, is most often limited by P and sometimes N concentrations in water (Gilliam, Logan & Broadbent, 1985; Lennox et al., 1997; Bolland, 1998). Although no standard for phosphate concentrations in freshwater, streams and lakes has been set, the risk of eutrophication is dependant on local environmental conditions (Corley, Frasier, Trlica, Smith & Taylor, 1999). The eutrophic threshold level below which algal growth is limited is considered to be in the region of 0.01 mg l^{-1} P. Numerous other researchers and environmentalists have expressed their concern regarding the environmental threat that P pollution poses to water resources, i.e. Ayoub (1999), Del Campillo, Van der Zee & Torrent (1999), Leinweber, Meissner, Eckhardt & Seeger (1999), Martin et al. (1999), Pote, Daniel, Nichols, Moore, Miller & Edwards (1999), Gale, Mullen, Cieslik, Tyler, Duck, Kirkchner & McClure (2000), Haygarth, Heathwaite, Jarvis & Harrod (2000) and Johnston (2000). A second threat to the environment concerning the use of P fertilizers is Cd pollution. Although the major source of anthropogenic Cd addition to soil is from sewage sludges and other industrial wastes, Cd is also added to soil with P fertilizers. Cadmium occurs naturally in PR at levels that vary with the source of the rock (Gilliam et al., 1985; Johnston, 2000).

Erosion

Phosphorus is strongly retained by soil and in the runoff process it is transported primarily as eroded sediment with lesser amounts as dissolved P (Gilliam et al., 1985). Runoff water extracts less from moist soil than from dry soil (Pote et al., 1999). Dissolved P is mostly immediately available for biological uptake (Sharpley & Rekolainen, 1997), but the amount of dissolved P in runoff water varies. During a field study on a silt loam with a clay content of 8 % at Booneville in the USA, a dissolved P content in runoff water of 0.57 mg l^{-1} during the month of May and 1.05 mg l^{-1} during the month of August, was measured (Pote et al., 1999). Because organic P concentration in the topsoil soil solution may be more than 20 times that of inorganic P, P lost from soils both in surface run-off and leaching can be in the organic state (Harrison, 1987). Phosphorus losses due to erosion in New Zealand from small catchment areas varies between 0.1 kg P ha^{-1} $year^{-1}$ for pastures to 6.3 kg P ha^{-1} $year^{-1}$ for row crops (Ward, O'Connor & Wei-Ban, 1990). Erosion losses of P should be limited by improved management practices (Sharpley & Rekolainen, 1997). For example, subsurface application of P will significantly reduce the runoff of orthophosphate (Randall, Wells & Hanway, 1985). Wolf (1999) accentuate the fact that wind erosion tend to remove a larger proportion of the fine particles, i.e. clay and organic material, which are richer in P than coarse soil particles.

Leaching

The extent of leaching losses is a function of the amount of water moving through the soil profile, the concentration of P in the soil solution, the P buffer capacity (PBC) of the soil and the total P immobilization capacity of the soil. Phosphorus leaching losses from the soil will increase under the following conditions, i.e. increasing amount of water moving through the soil, increasing concentration of P in solution, decreasing PBC and increasing P saturation of the soil (Holford, 1976; Soon, 1985). Although leaching losses occur from peat soils (Mengel & Kirby, 1987) and from very sandy soils (Wolf, 1999), the loss of P from most soils, especially those with a high P fixation capacity, is negligible (Larsen, 1976; Soon, 1985; Mengel & Kirby, 1987; Wolf, 1999), i.e. less than 0.44 kg P ha^{-1} $year^{-1}$ (Simpson, 1991), unless the soils become P saturated following P applications over several years. However, continuous P applications do not necessary lead to P saturated soils (Cisse & Amar, 1999). The P retention capacity (PRC) of soil, especially in the lower horizons, is great enough to retard the movement of even very heavy applications of P in the form of fertilizer, manure or sewage sludge. In most instances, most P applied is retained near the soil surface when the fertilizer is not incorporated or placed within the surface layer after plowing. During a study it was found that biannual applications of super phosphate to permanent pasture penetrated no more than 57 to 75 mm after 16 years. It was also recorded that a surface application of 600 kg P ha^{-1} of super phosphate penetrated the soil only 30 mm deep. During a no-till experiment, applications of 268 kg P ha^{-1} over a three year period increased the extractable P at least 10-fold in the 0 to 50 mm depth, but showed no increase below that zone. Thus the greatest potential for movement of P to groundwater is from the application of large quantities of P to soils with low P retention capacity, such as sands or organic soils. When 600 to 2000 kg P ha^{-1} as super phosphate was applied to fine sand, P was leached to depths up to 2 m, with the greatest accumulation in the 150 to 450 mm zone. When 13000 kg P ha^{-1} as monocalcium phosphate (MCP) was applied to the same soil, 22 % was retained in the surface 150 mm, with P movement up to 4 m deep (Gilliam et al., 1985). In Western Australia, in the areas receiving more than 450 mm rainfall, applied P has been found to leach from sands with low P adsorbing capacities, i.e. low clay content (less than 5 %) as well as low Fe- and Al-oxide contents (Bolland, 1998). However, care should be taken not to confuse P movement within soils as a result of leaching with that as a result of cultivation. During a field experiment over a period of eight years on different soils in Minnesota, it was found that a mouldboard plough distributed extractable soil P evenly throughout the 0 to 300 mm soil layer, while the chisel plough, disk and no-till practices kept almost all the applied P within the 0 to 150 mm soil layer, with only a small fraction incorporated into the deeper 150 to 300 mm layer (Randall et al., 1985). The various processes that contributes to the loss of P from agricultural land were also discussed by other authors, i.e. Lennox et al. (1997), Morgan (1997), Sharpley & Rekolainen (1997), Addiscott & Thomas (2000) and Johnston (2000).

Volatilization

Volatilization of P does not really contribute to P losses from the soil (Ross, 1989; Wolf, 1999).

2.3.2 Phosphorus transformation processes

2.3.2.1 Biological processes

Phosphorus mineralization and immobilization are similar to those of N in that both processes occur simultaneously in soils (Alexander, 1977; Addiscott & Thomas, 2000) and are likewise affected by various factors (Wolf, 1999). It is thus difficult to describe the processes as depicted in Figure 2.2 separately, however, an attempt to do so will be made in this section.

2.3.2.1.1 Mineralization

As the total amount of P in soils is small and at low concentrations, mineralization of the organically bound P, with a consequent release of inorganic P, is of major importance in P cycling and the maintenance of P available to plants. Only a small amount of organic P in soils needs to be mineralized in order to provide a substantial proportion of the requirements of crops or natural vegetation (Harrison, 1987). The mineralization of organic matter and hence organic P in soil is largely due to the combined activities of soil micro-organisms and free enzymes, phosphatases as well as intracellular enzymes released due to the lysis of microbial cells present in soil. The factors that regulate the activity of micro-organisms thus mainly govern the mineralization of organic P in soil (Dalal, 1976; Alexander, 1977; Volk & Loeppert, 1982; Wolf, 1999).

$$\text{Organic P} \quad \underset{\text{Immobilization}}{\overset{\text{Mineralization}}{\rightleftharpoons}} \quad \text{Inorganic P } (H_2PO_4^- \,/\, HPO_4^{2-})$$

Figure 2.2 : The process of mineralization and immobilization (Anon, s.a.; Havlin et al., 1999).

Measuring organic P cycling in soils is more difficult than for N, because inorganic P produced through mineralization can be removed from solution by P adsorption to clay and other mineral surfaces and P precipitation as secondary Al-, Fe-, or Ca-P minerals. However, the quantity of P mineralized during a growing season varies widely among soils (Havlin et al., 1999). The majority of factors that will influence P mineralization are soil related, i.e. the organic matter and hence organic P content and rate of breakdown, which depend on the ratio between organic C and P, together with the PRC of the soil, soil temperature (optimum temperature for growth of most bacteria is between 30 and 45 °C), soil pH, liming, soil moisture content and alternate wetting and drying. Biological related factors are phosphatase activity and the presence and type of micro-organisms. Other factors are the presence of plants, application of fertilizers and cultivation intensity. The influence of the mentioned factors on P mineralization is discussed by various authors, i.e. Beever & Burns (1976), Dalal (1976), Godwin & Wilson (1976), Alexander (1977), Campbell & Souster (1982), Moghimi, Lewis & Oades (1985), Murdoch, Jackobs & Gerdemann (1985), Sanders & Tinker (1985), Harrison (1987), Mengel & Kirby (1987), Garrity, Mamaril & Soepardi (1990), McLaughlin, Malik, Memon & Idris (1990), Havlin et al. (1999) and Wolf (1999).

2.3.2.1.2 Immobilization

Immobilization of P is reported the second major factor responsible for fertilizer P accumulation in soils. Soils vary widely in their capacity to immobilize P, but with the exception of the most sandy soils, most agricultural soils can immobilize more P than is normally applied in fertilizer (Holford, 1976). Immobilization of inorganic P, by its conversion to organic forms, occurs in most soils and is related to the metabolic activity of soil micro-organisms, but the quantities vary widely, with values of 25 to 100 % of applied P being reported. Continued fertilizer P applications can increase the organic P content and subsequently increase P mineralization, i.e. increases of 3.4 to 11.2 kg ha^{-1} $year^{-1}$ in organic P with continued P fertilization are possible. Suppression of microbial activity within soils by autoclaving, irradiation, or addition of toluene often reduces the amount of immobilization, but not always. Conditions promoting the synthesis of organic P by micro-organisms are complex. It is generally considered that immobilization is likely to surpass mineralization when the C/P ratio in soil is 200:1. However, the C/P ratios at which immobilization occurs, vary. Maximum immobilization appears to occur at a temperature of 30 °C, though it can proceed at temperatures as low as 5 to 7 °C and even lower. Usually within a few days or weeks of being immobilized, microbially bound P is recycled through mineralization, but often a substantial amount of immobilized organic P still remains so for a considerable period, even up to several months. It is suggested that recently immobilized organic P enters the "active" fraction within the soil organic matter pool, but eventually, during humification, it becomes part of the stable "passive" fraction, subsequently remaining unaffected by plant growth and unchanged by pedogenesis (Harrison, 1987).

2.3.2.2 Physico-chemical processes

As organic P is mineralized to inorganic P or as inorganic P is added to soil, the inorganic P in solution not absorbed by plant roots or immobilized by micro-organisms is subjected to various retaining processes (Havlin et al., 1999). In the literature various terms are used to describe the mostly chemical, but also physical P retaining processes. It seems as if researchers are generally lax by using some terms collectively, rather than separately or even physically and chemically correct, to describe specific processes, and in this careless manner, create confusion.

Retention or fixation comprises all the processes and reactions with soil constituents which reduce the availability of applied P to crops. Sorption, viz. either absorption or adsorption and precipitation are therefore prominent processes of retention or fixation (J. Beaton, 2001, Kelowna, British Columbia, Canada: Personal communication). Some researchers consider retention or fixation of applications of soluble P to be a continuous sequence of sorption and precipitation (Bolland, 1998). Thus retention or fixation can be defined as the process or processes in soil by which certain chemical elements essential for plant growth are converted from an available to unavailable form (Van der Watt & Van Rooyen, 1995).

The term sorption is used when uncertain if the retained P is either absorbed or adsorbed, or perhaps a combination of both (J. Beaton, 2001, Kelowna, British Columbia, Canada: Personal communication). According to Van der Watt & Van Rooyen (1995) the general term sorption, refers to adsorption by both physical and chemical forces. In a system containing two or more components, a substance may be concentrated or depleted in the neighbourhood of a surface. If a substance is concentrated in the neighbourhood of a surface, it is said to be positively adsorbed. If the concentration of the substance is lower in the interfacial region than in bulk, it is said to be negatively adsorbed (Alberty, 1983). Thus, the accumulation of particles at a surface is called adsorption, the substance that adsorbs is the adsorbate and the underlying material is the adsorbent or substrate (Hawley, 1977; Parker, 1983; Atkins, 1986). Adsorption occurs either as physical or chemical adsorption (Alberty, 1983). Physical adsorption or physisorption is reversible adsorption by weak long range Van der Waals interaction between the adsorbate and the substrate. With no covalent bonds and the energy released when a particle is physisorbed is of the same magnitude as the enthalpy of condensation (Atkins, 1986), i.e. usually less than 15 to 20 kcal mole^{-1} or 63 to 84 kJ mole^{-1} (Parker, 1983). Chemical adsorption or chemisorption is adsorption involving stronger interaction between adsorbate and adsorbent usually accompanied by rearrangement of atoms within or between adsorbates. Reaction occurs between the surface of the adsorbent and the adsorbate. Heats of chemisorption are usually in excess of 20 to 30 kcal mole^{-1} or 84 to 126 kJ mole^{-1} (Parker, 1983; Atkins, 1986). The process of adsorption can be described by the Langmuir isotherm (Lawton, 1961; Alberty, 1983; Parker, 1983; Atkins, 1986). Adsorption of P occurs particularly on the surfaces of hydrous oxides of Al and Fe, occurring as discrete particles or as films on clay and as impurities in $CaCO_3$ while absorption of P happens when the retained P penetrates more or less uniformly into solid soil constituents (J. Beaton, 2001, Kelowna, British Columbia, Canada: Personal communication).

Precipitation is the process of producing a separable solid phase within a liquid medium by gravity or as a result of a chemical reaction (Hawley, 1977). In a broad sense, precipitation represents the formation of a new condensed phase, although other terms are often used to describe the process (Parker, 1983). Thus, high initial concentrations of P released during dissolution of P fertilizer granules or from droplets of liquid P sources, react with soil constituents to form secondary minerals. These secondary minerals are Fe/Al-P compounds in acid soils while in neutral and calcareous soils the precipitates are Ca/Mg-P compounds (J. Beaton, 2001, Kelowna, British Columbia, Canada: Personal communication). In general, in soils rich in Al and Fe oxides, as well as in clay minerals, P desorption seems to be the more dominant process, whereas in poor sandy, calcareous and especially organic soils, P precipitation plays a major role (Mengel & Kirby, 1987).

Until recently it was believed that P retained or fixed by soil went over into plant unavailable forms. Experiments have shown that in many soils, reserves of plant available P can be built-up over time. Soils enriched by P reserves frequently gave larger yields than soils without the reserves. Hence the low plant uptake figure of 15 % for P underestimates the long-term efficiency of P fertilizers (De Larderel & Maene, 1998). Phosphorus sorption is a complex process that cannot be considered as independent from other physico-chemical processes in the soil and is seen as a continuum, with some ions loosely held, but most of them chemically strongly sorbed. Both inorganic and organic P ions move within the continuum and equilibrium will be reached if the system is left undisturbed (Addiscott & Thomas, 2000). Therefore an understanding of the reactions between P and soil constituents is of great importance since the availability of P to plants is largely determined by these. Influencing these reactions would enable us to increase the efficiency of utilization of fertilizer P by plants (Rajan, 1976).

2.3.2.2.1 Sorption

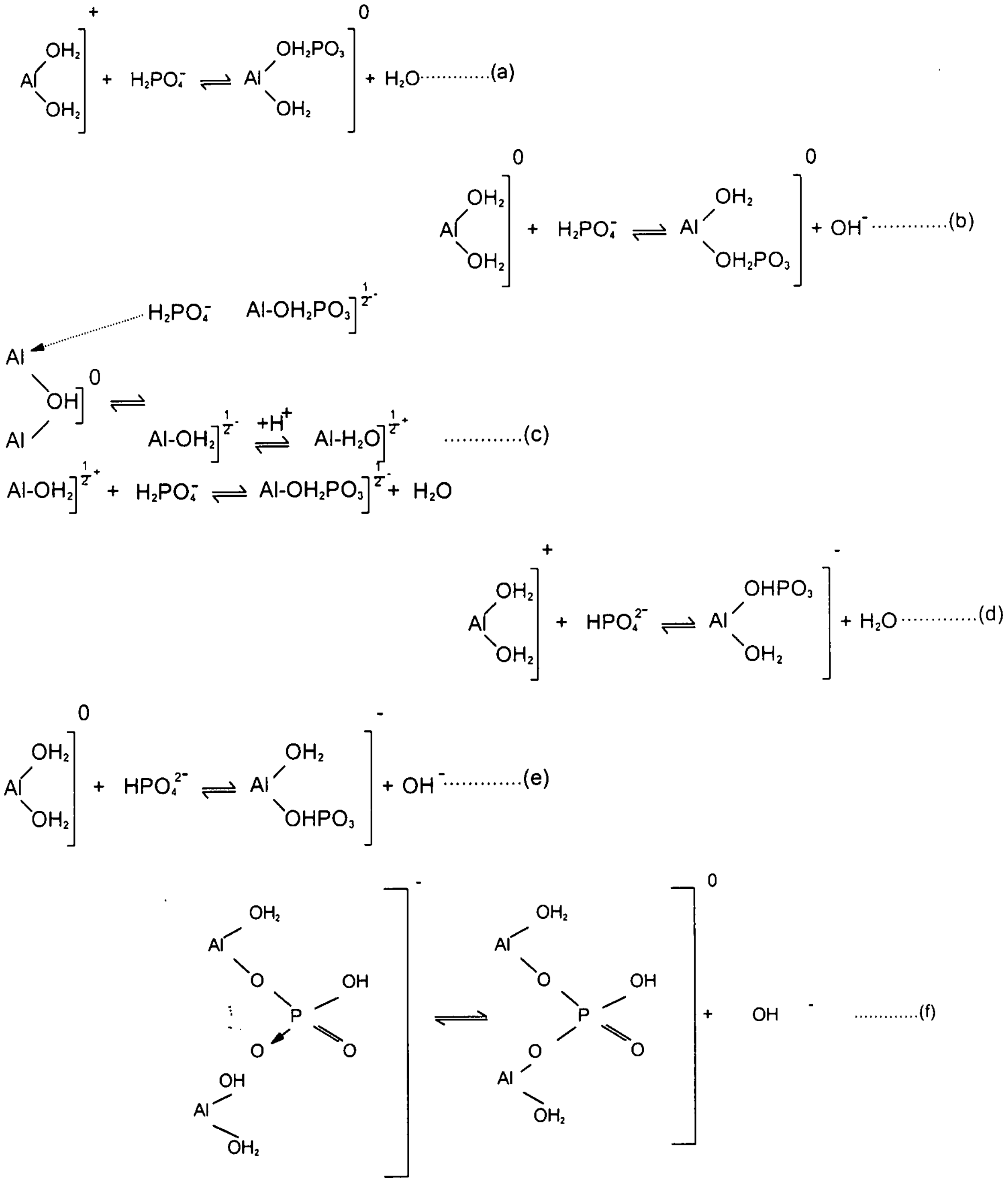
Many soil physical and chemical properties influence the solubility and sorption of P in soils. The majority of factors are soil related, i.e. concentration of the soil solution, parent material, type of mineral surfaces (Fe/Al oxides or clays), surface charge, surface areas, P sorption value, dominant cation on the cation complex, pH and electrolyte concentration, extent of P saturation, cation and anion effects, organic matter and organic P content of the soil, repeated additions of P, desorption, flooding and oxygen supply (Sibbesen, 1981; Mattingly, 1985; Mengel & Kirby, 1987; Barrow, 1990; Blair, Freney & Park, 1990; Syers & Ru-Kun, 1990; Wada, Xue-Yuan & Moody, 1990; Morgan, 1997; Havlin et al., 1999; Addiscott & Thomas, 2000; Anon, s.a.). Fertilizer related factors are the P fertilization history, i.e. application level and type of fertilizer used (Ryden, Syers & Gregg, 1976; Barrow, 1990; Havlin et al., 1999). Management related factors are cultivation and liming practices (Ryden et al., 1976; Mengel & Kirby, 1987; Kamprath & Foy, 1985; Bolland, 1998; Addiscott & Thomas, 2000). Other factors are time and temperature (Barrow, 1990; Havlin et al., 1999).

2.3.2.2.1.1 Metal hydrous oxides

Regardless of pH, all mineral soils contain Al and Fe oxides and hydrous oxides, which occur as discrete particles or as coatings on other soil particles, especially clay. In addition, amorphous Al hydroxy compounds may be present in interlayer locations of expandable Al silicates. Such materials are highly efficient in adsorbing $H_2PO_4^-$ ions that may be present in the soil solution (Morgan, 1997). Several short-range order Fe- and Al-P compounds appear to form in soils when MCP is added, and may slowly crystallize to strengite and variscite. Such compounds seem unlikely to persist, and their importance as a controlling influence in P cycling seems to be limited (Syers & Ru-Kun, 1990). When goethite (FeOOH) comes into contact with orthophosphate ions in aqueous solution, there is a very rapid reaction involving exothermic ligand exchange between the ions and the reactive surface groups. A hydroxyl ion or a water molecule is released from the surface, and a phosphated surface complex is formed. The sorption sites for inositol hexaphosphate and inorganic orthophosphate in acid soils was found to be the same, but with sorption preference to inositol hexaphosphate over inorganic orthophosphates (Addiscott & Thomas, 2000).

An important electrochemical property of these oxides is that, while they possess a constant surface potential, their surface charge varies depending on the suspension pH. The pH value at which the pure oxides carry no nett charge is usually above pH 8. In acid and neutral soils, the oxides invariably carry nett charge with positive and neutral sites on their surface. At a constant pH, monovalent phosphate is adsorbed on positive sites displacing water that was coordinated to the oxide surface, with neutralisation of the positive charge (Figure 2.3a). On neutral sites adsorption is by displacement of hydroxyl groups without change of surface charge (Figure 2.3b). When the adsorption sites on the surface are saturated ($\theta = 1$), the hydrous oxide carries no nett charge. Additional adsorption evidently occurs by the disruption of hydrous oxide polymers into smaller units with a concomitant increase in adsorption sites. Adsorption of phosphate on this new surface has been found to make the surface negative (Figure 2.3c). The hydrous oxide polymers are not disrupted before the near complete saturation of the original surface adsorption sites. In contrast to the monovalent ion, indirect evidence indicates that the divalent phosphate is adsorbed both in the linear form and as bridging ligand even at a short reaction time of three hours. When it is adsorbed in linear form, either on positive or neutral sites, the sites become negatively charged (Figures 2.3d and 2.3e). However, when the adsorbed divalent ion is rearranged as a bridging ligand the charge of the particular site is altered from negative to neutral (Figure 2.3f). Once the surface is saturated, the Al polymers are disrupted, but the divalent phosphate seems to be adsorbed on these new sites only as bridging ligands, the final product being similar to that in Figure 2.3f. However, the surface would acquire one negative charge for each ion adsorbed (Rajan, 1976).

According to Addiscott & Thomas (2000) the behaviour of 20 tropical and 20 British acidic soils, using the "anion exchange capacity" of Piper (1942) and sorption index of Bache & Williams (1971) were studied. These indices were related to soil pH, clay content, C content, free Fe oxides (dithionite-citrate extraction) and extractable Al (acidified ammonium acetate), finding no differences between the tropical and British soils. Sorption was well correlated with extractable Al and free Fe oxides, where the correlation with free Fe oxides being the stronger in the freely drained British soils, but not in the poorly drained ones.



Figures 2.3 : Phosphorus sorption on metal hydrous oxides at (a) constant pH, (b) on neutral sites, (c) on negative sites, in linear form on (d) positive and (e) negative site and (f) when an ion is rearranged as a bridging ligand (Rajan, 1976).

Sorption also correlated well with C in the poorly drained British soils and in the tropical soils when sorption was estimated using a large P concentration. The relationships with pH and clay were not strong. When a group of pedological similar soils with differing pH values were examined, a highly significant decrease in P retention, with increasing pH, were found. To some extent this was associated with decreases in exchangeable and acetate-extractable Al.

2.3.2.2.1.2 Aluminium silicates

Amorphous Al silicates, viz. the allophanes, are the dominant minerals in the clay fraction of the soils from volcanic ash and are also present as coatings on crystalline clay minerals in other soils. Because of their very high reactivity they are highly sorptive for P (Addiscott & Thomas, 2000). The capacity of Al silicates to sorb P varies with the degree of silication of the gels. Sorption by Al silicates take place by means of two mechanisms, i.e. adsorption both by surface ligand exchange and by disruption of Al hydrous oxide polymers as with the pure hydrous oxide systems, and sorption by displacing clay structural silicate (Si_{st}). In a natural allophane clay, Si_{st} displacement accounted for 5 % of P retained at θ-values < 1, whereas at higher θ-values it accounted for 11 % (Rajan, 1976).

The principal types of crystalline Al silicates are kaolinitic (1:1) and montmorillonite (2:1) clays. At low concentrations of P (less than 0.3×10^{-3} M), phosphate is adsorbed on these clays on Al atoms situated at the edge face of crystals. At high θ-values, Si_{st} is displaced as from the amorphous Al silicates. In a kaolinitic soil, it was found that Si_{st} displacement accounted for 14 % of P retained at θ-values > 1. In a montmorillonitic soil, Si_{st} displacement accounted for 13 % of P retained up to θ-values = 1, and 45 % beyond that point (Rajan, 1976).

2.3.2.2.1.3 Calcium carbonates

Calcium carbonates dominate the chemistry of calcareous soils (Kissel, Sander & Ellis, 1985) and the importance of P sorption in these soils is well known (Rajan, 1976; Addiscott & Thomas, 2000). Phosphorus is one of the essential elements for plant nutrition that may have limited availability in calcareous soils. Their sorption capacities are between that of crystalline clay minerals and hydrous oxide, although Ca-kaolinite may adsorb more P than $CaCO_3$. Phosphorus fixation or retention on $CaCO_3$ is initially a rapid monolayer adsorption and this is followed by precipitation at high concentrations (Rajan, 1976). In Ca systems, P is sorbed onto a calcite surface which leads to the precipitation of MCP. If sufficient soluble P is added to a calcareous soil and P is initially reversibly adsorbed on calcite, rapid formation of dicalcium phosphate dihydrate (DCPD), will take place. As the concentration of P is lowered in the solution with time, the DCPD will dissolve and octacalcium phosphate (OCP) will form. When all the DCPD has dissolved, the amount of P in the soil solution will be controlled by OCP. When the amount of P in the soil solution will no longer support OCP, it will dissolve and hydroxyapatite (HA) will form. The last compound is least soluble in water and if HA is the stable form in a particular soil, this will be the final Ca-P compound formed and will represent the lower limit of P in the soil solution and the lower limit of P available to plants (Syers & Ru-Kun, 1990; Addiscott & Thomas, 2000). Consequently, the availability of P to plants will be controlled by the rate of application of soluble P, which controls the Ca-P compounds formed and the rates of transformation from one compound to another (Patrick, Mikkelsen & Wells, 1985; Morgan, 1997).

2.3.2.2.2 Desorption

Desorption can be defined as the process of removing an adsorbed material from the solid on which it is adsorbed, i.e. the reverse of adsorption. Desorption may be accomplished by heating, reduction of pressure, the presence of another strongly adsorbed substance, or by a combination of these means (Hawley, 1977; Atkins, 1986). Thus, desorption describes the release of adsorbed P into solution (Syers & Ru-Kun, 1990) and is therefore of interest to plants. Desorption of anions is only possible if the surface is made more negative than the equilibrium value at which adsorption takes place. Anions capable of specific adsorption to a greater extent than the adsorbed anion can make the surface more negative, liberating OH^- ions, which results in desorption. Desorption of anions varies between complete reversibility and complete irreversibility and ceases when the charge on the surface reaches its original value, where the nett surface charge will then be in equilibrium with H^+ and OH^- in solution, but the adsorbed anion makes no contribution to the charge. The surface now behaves as though the anions were not present, presumably because the binding energy of the anion to the surface is very high relative to the binding energy of the ions that balance the charge. Desorption therefore can take place only when the adsorbed anions confer a negative charge to the oxide surface. The same effect is achieved by raising the pH, thus increasing the adsorption of OH^- ions. Specific adsorption of an anion always involves the formation of a coordination complex on the oxide surface, made possible by the presence of protons either on the oxide surface, at pH values more acid than the zero point of charge, or derived from the dissociation of a weak acid (Mattingly, 1985; Addiscott & Thomas, 2000). However, little information on desorption is available.

2.4 Phosphorus in plants

2.4.1 Uptake and function of phosphorus in plants

Phosphorus is one of three quantitatively prominent nutrient elements which are absorbed by plant roots as complex anions, viz. as ortho-phosphate, either as $H_2PO_4^-$ or HPO_4^{2-} (Epstein, 1972; Lüttge & Higinbotham, 1979; Soon, 1985; Young et al., 1985; Simpson, 1991; Havlin et al., 1999; Johnston, 2000; Anon, s.a.). The former ion is absorbed at a rate that is nearly 10 times faster than that of the latter. Other forms of P, both organic and inorganic, may be absorbed by plants under certain conditions but are of little practical significance (Young et al., 1985). The rate of uptake is up to a certain limit directly proportional to the concentration in the immediate vicinity of the active roots. This means that plant uptake is to a considerable extent dependent on transport processes in the soil (Anon, s.a.).

Phosphorus has an absolutely vital role in the plant, being part of the cell nucleus, essential for cell division and, therefore particularly important at the growing points of the plant, i.e. the meristematic tissue. It occurs in phospholipids including those of membranes, in sugar phosphates, various nucleotides and coenzymes and regulates many enzymic processes, for instance during the fascinating and complex conversion of water and CO_2 to sugars and starches in the process known as photosynthesis. It is a key portion of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) molecules containing the encoding for protein formation and cellular genetic information. It thus has a vital role in the breakdown of the carbohydrates and other foods produced by photosynthesis in the plant. As it is incorporated in adenosine triphosphate (ATP), it is part and parcel of the universal "energy currency" of all living cells of whatever species and therefore plays a key role in energy metabolism and transfer. Almost every metabolic reaction of any significance proceeds via phosphate derivatives. The turn-over time of the terminal phosphate group on a ATP molecule is measured in fractions of a second, suggesting that phosphate concentrations could change rapidly during periods of intense microbial activity, involving small amounts of P in these changes. As P is important as a stimulus to root development, roots branch out and root hairs form profusely in the vicinity of a source of P. Thus, owing to its effects on roots, P is a major factor in determining the early growth of a plant and its vigour throughout the season (Lawton, 1961; Epstein, 1972; Lüttge & Higinbotham, 1979; Munson, 1982; Parnes, 1990; Simpson, 1991; Bolland, 1998; De Larderel & Maene, 1998; Havlin et al., 1999; Wolf, 1999; Addiscott & Thomas, 2000). Phosphorus therefore favours crop quality (especially certain fruit, vegetable and grain crops), resistence of young plants to low temperature (frost), reproductive phase of plants (for example the maturity and quality of fruits and seeds, as well as the mineral content of feeds and forages), optimal rate of N to be used without risk of upsetting the vegetative cycle or prejudicing, speed of establishment of young plants and optimum planting population (Anon, s.a.; Havlin et al., 1999), absorption of Mo by plants (Epstein, 1972), early maturity (particularly grain crops as ample P nutrition reduces the time required for grain ripening), greater straw strength in cereals and raising the tolerance of small grains to root diseases (Havlin et al., 1999). In vegetables crops, P influences market quality, particularly size and grade and under P deficient conditions, the fruit size is often decreased and does not meet acceptable size criteria (Young et al., 1985). The importance of P in plant nutrition was also discussed by other authors, i.e. Price (1976), Bidwell (1979), Mengel & Kirby (1987) and Sposito (1989).

Plant P uptake is largely governed by three major factors, i.e. the type of plant, the stage of plant maturity and the competition between the plant roots and soil chemicals for soil and fertilizer P (Jones, 1982), but are furthermore catalyzed by the amounts of P already removed, soil moisture, pH, P cation type, cation exchange, aeration, soil depth and the climatic factors of rainfall, temperature and solar radiation (Nye, 1969; Parnes, 1990; Simpson, 1991; Wolf, 1999; Anon, s.a.). The concentration of phosphate anions in the soil solution is usually low, because of fixation or retention reactions (Mengel & Kirby, 1987; Simpson, 1991; Morgan, 1997). Therefore the uptake of fertilizer P depends much on root growth and the root morphology of the crop being considered (Mengel & Kirby, 1987). As the P concentration in solution decreases through uptake, there must be a mechanism whereby the soil solution is replenished through a combination of dissolution and desorption reactions, in order that P uptake be sustained over time. The replenishment involves reaction products from the most recent P fertilizer application and soil P compounds, resulting from historical P fertilizer applications (Nye, 1969; Sutton & Gunary, 1969; Godwin & Wilson, 1976; Shapiro & Fried, 1985; Morgan, 1997; Anon, s.a.). The capability for active uptake of P differs between plant species and may even differ between cultivars of the same species. In studies it was found that P was absorbed by lettuce only from the upper 0 to 180 mm soil layer, while carrots utilized a considerable portion from the 300 to 400 mm layer and also 10 % of the total uptake from the soil deeper than 1 m (Mengel & Kirby, 1987). Plants with extensive roots systems, such as maize, absorb P from a larger soil volume and are therefore able to obtain sufficient P from the soil than many other plants with limited root systems (Jones, 1982). The recovery of available soil and fertilizer P by plants is quite low, i.e. the recovery efficiency of fertilizer P amounts to only 10 to 30 % of that added immediately prior to planting the crop (Blair et al., 1976). Furthermore, by the time plants have produced about 25 % of their total dry weight, they have accumulated as much as 75 % of their P needs (Jones, 1982) or according to Young et al. (1985) plants often absorb 50 % of the seasonal total demand by the time they accumulate 25 % of the total seasonal dry matter. Since the loss of P in percolating waters is very small, the 70 to 90 % that is not absorbed by the plants remains immobile in the soil unless it is lost by erosion. Plants vary widely in their ability to obtain sufficient P from soils testing low in available P (Jones, 1982). In Australia, it was found that when bicarbonate extractable P in soil was higher than 35 mg kg^{-1}, the soil was non-responsive to P. Those soils with extractable P less than 35 mg kg^{-1} were responsive to P applications, irrespective of parent material and past history. On sandy soils in the southern parts of Australia, the critical value was between 32 and 38 mg kg^{-1} (Blair et al., 1976).

As not all soil P is plant available (Johnston, 2000), only three main soil P fractions are important in terms of plant nutrition, i.e. P in soil solution, the labile and the non-labile pool (Mattingly, 1985; Mengel & Kirby, 1987; Havlin et al., 1999: Anon, s.a.). The different pools and relative sizes as reported by Mengel & Kirby (1987), as well as numerous other literature sources, are presented in Figure 2.4. Phosphorus in soil solution was already discussed. The P in the labile pool is the fraction of solid P which is held on surfaces so that it is in rapid equilibrium with soil solution P. It consists mainly of soluble Ca-P and adsorbed P. Of the adsorbed P only the mononuclear fraction is considered to be labile, the binuclear fraction being held very strongly by the adsorbing surfaces. This labile fraction is in rapid equilibrium with the soil solution (Larsen, 1985; Schofield, 1985; Mengel & Kirby, 1987; Havlin et al., 1999)

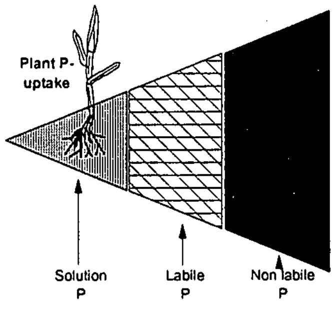


Figure 2.4 : Different pools and relative sizes of P sources to plants (Reconstructed from Anon, s.a. and Mengel & Kirby, 1987).

2.4.2 Detrimental effects of phosphorus deficiency on plants

Contrary to popular opinion, P deficiency is probably the most difficult major nutrient deficiency to identify visually. As P deficiency affects early growth, the symptoms usually are expressed in restricted early growth as P deficient plants develop slowly and are often stunted and retarted in growth with delayed maturity. Loss of older leaves, anthocyanin development in stems and leaf veins, and in extreme cases, the development of necrotic areas in various parts of plants, may also occur. The deficient plants have few, small leaves and the older leaves die and wither away. As the season progresses, deficiency symptoms become more obvious. Thus, the effect of P deficiency appears in the colour and vitality of the plant (Lawton, 1961; Epstein, 1972; Bidwell, 1979; Jones, 1982; Munson, 1982; Mengel & Kirby, 1987; Parnes, 1990; Farina, Manson & Johnston, 1993; Bolland, 1998; Wolf, 1999; Anon, s.a.).

As P deficiency may delay the growth of new shoots and the development of flowers, the formation of fruits and seeds are depressed, thus not only low yields, but also poor quality fruits and seeds, are obtained, as well as a reduction in the number and size of seeds. Thus, acutely deficient plants produce because of poor shoot and root development little or no seed or grain. In cereals tillering is affected and may be reduced. Phosphorus deficient maize is usually described as having red or purple leaf and stem discolourations originating from an enhanced formation of anthocyanins that, because of the great mobility of P, manifests usually first in the older leaves sometimes with red, purple, or brown pigments, especially along the veins. Leaves also tend to become darker green or else chlorosis spreads to the leaf veins as well as the lamella with tips dying, or purple (Epstein, 1972; Bidwell, 1979; Munson, 1982; Mengel & Kirby, 1987; Parnes, 1990; Farina et al., 1993; Bolland, 1998; Härdter & Krauss, 1999; Havlin et al., 1999; Wolf, 1999; Anon, s.a.). According to Farina et al. (1993) such symptoms do occur, but only on plants suffering from extremely severe P deficiency. Thus, usually when this type of symptom becomes visual, as it is already very severe, it is no longer generally curable and will have a disastrous effect on harvest. Between a healthy state and deficiency, there exists intermediate conditions which are evidenced by less vigorous growth and a noticeable loss of yield and which are difficult to identify other than by foliar analysis (Anon, s.a.). Occasionally, certain cultivars will show some red discolourations during early growth if the weather is cool (Jones, 1982; Farina et al., 1993), and also if plant roots are unable to reach the fertilizer band, but the most common visual symptom of P deficiency is a lighter green colour which is easily confused with the early stages of N deficiency, and difficult to recognize without the comparison provided by adjacent well-fed plants (Farina et al., 1993). In some species, genetic characters may also be responsible for purple colour (Jones, 1982). According to Simpson (1991) the purple colours can also result from numerous other causes, i.e. water-logging, drought, Mg deficiency and nematode attack. Where economically justifiable, P deficiency is alleviated through the application of appropriate amounts of P fertilizer to the soil (Bidwell, 1979; Jones, 1982; Harrison, 1987; Bolland, 1998; Schmidt & Fleming, 1998; Wolf, 1999). In P deficient soils, increasing applications of P per unit area produce spectacular increases in yield (Anon, s.a.).

A direct relationship exist between P deficiency and soil pH. When basic materials such as limestone are added to a soil with a neutral pH, the availability of Ca-P will be decreased. On the other hand, additions of limestone to acid soils, which contain Fe- and Al-P, will increase the P availability by the formation of more soluble Ca-P (Beaton, Fox & Jones, 1985). Extremely high P levels in the root medium can depress growth and may reduce the availability, uptake and translocation of some of the micro nutrients, i.e. Fe, Mn, and Zn, with the deficiency of Fe and Zn being most common (Mengel & Kirby, 1987; Wolf, 1999). Excesses are common in soil subject to heavy P fertilization, particularly if Al is low. It is suspected that immobilization of the micro nutrients by P may take place at the roots and also within the conducting tissues. It is suspected that the deficiencies of Cu and Zn caused by excesses of P may be due in part to the precipitation of these elements by phosphates (Wolf, 1999).

2.4.3 Sources of phosphorus utilized by plants

High-yielding crops require ample amounts of available P throughout the growing season (Jones, 1982) that may be supplied by different sources, i.e. seed, soil, atmosphere, manures and fertilizers (Simpson, 1991; Bolland, 1998). As phytic acid, the hexaphosphate ester of myo-inositol, or its Ca or Mg salts (phytin), serve as a storage form of P in seeds (Epstein, 1972; Havlin et al., 1999) and in the very early stages of growth, the plants draw much of their nutrient supply from their own seed (Munson, 1982; Parnes, 1990; Bolland, 1991; Simpson, 1991). This source, however, is rapidly depleted even in crops such as potatoes. The plant with its rapidly developing root system must then depend upon what it can obtain from the soil or from supplements (Simpson, 1991; Bolland, 1998). Concentrations in excess of 0.3 % P in the seed of cereal crops, lupines and pasture legume species are usually adequate for early growth. Concentrations of less than 0.2 % P in the seed can reduce yields by up to 70 % during early growth.

2.4.4 Movement of phosphorus from soil to plant roots

In P nutrition of higher plants, the most important single event happens at the interface between soil and root as it is here that inorganic P ions are taken from the soil solution near to the root surface into the cytoplasm of the root cells, but to be absorbed, they must come into contact with the root surface. Absorption is accomplished in three ways, i.e. root interception, mass flow and diffusion (Sutton & Gunary, 1969; Bieleski, 1976; Godwin & Wilson, 1976; Jones, 1982; Narayanan & Balakrishna Reddy, 1982; Nye, 1985; Havlin et al., 1999).

Root interception

The total amount of dissolved P in the root penetrated soil profile is in the order of 0.1 to 1.0 kg ha^{-1}. As normal crops must take up 15 to 30 kg P ha^{-1} during a few months it is obvious that the P content of the soil solution must be frequently renewed from the solid phases during the vegetation period (Anon, s.a.). The importance of root interception as a mechanism for ion absorption is enhanced by the growth of new roots throughout the soil and perhaps also by *Mycorrhizal* infections. In studies on maize inoculated with *Endomycorrhiza* with and without added P fertilizer, the shoots of maize not inoculated contained 2970 and 750 µg P in their shoots, respectively, while those inoculated contained 5910 and 1340 µg P in their shoots, respectively. As the root system develops and exploits more soil, soil solution and soil surfaces retaining adsorbed ions exposed to the root mass, and absorption of these ions occurs by a contact exchange mechanism (Jones, 1982; Havlin et al., 1999; Johnston, 2000). The quantity of nutrients that can come in direct contact with plant roots is the amount in a volume of soil equal to the volume of roots. Roots usually occupy 1 % or less of the soil, although roots would contact a maximum of 3 % of the available soil nutrients (Havlin et al., 1999). The degree of division of the root system is of importance in determining soil exploration and thus contact with soil P. It was recorded that P efficiency in maize varieties was directly related to the higher ratio of secondary to primary roots (Godwin & Wilson, 1976). As active plant roots can quickly deplete the P in solution in their immediate vicinity, their subsequent P supply then depends on release from the solid phase and diffusion to the root surface (Sutton & Gunary, 1969).

Mass flow

Movement of ions in the soil solution to root surfaces by mass flow is an important factor in supplying nutrients to plants (Anon, s.a.; Havlin et al., 1999). As large volumes of water entering roots (Jones, 1982; Olsen, Kemper & Jackson, 1985) as a result of transpirational water uptake by the plant, mass flow occurs when plant nutrient ions and other dissolved substances are transported in the water. The amounts of nutrients reaching roots by mass flow are determined by the rate of water flow or the water consumption of plants and the average nutrient concentrations in the soil water (Havlin et al., 1999). Broadcast fertilizer applications, which build up nutrient supply throughout the root zone, favour nutrient uptake depending primarily on mass flow (Jones, 1982). Therefore, in soils with high P levels, resulting from broadcast fertilizer applications, mass flow accounts for much greater transfer of P to the root surface than diffusion. Mass flow can also play a part in the transport of P towards plant roots (Anon, s.a.; Mengel & Kirby, 1987). Therefore, in soils with low P levels, mass flow provides only a small portion of the P requirement. In fertilized soil with a solution P concentration of 1 mg kg^{-1} (Olsen et al., 1985) mass flow contributes 20 % of the total requirement (Havlin et al., 1999). According to Anon, (s.a.) mass flow of soil solution is of secondary importance for the plant uptake of P, since the capacity of the solid phases to deliver P ions rapidly and with staying power is of utmost importance for the plant uptake.

Diffusion

The diffusion of P to the root surface is a major limiting step in the uptake of this nutrient. The slow rate of diffusion of P in soil is highlighted by a comparison of the apparent diffusivity factors between phosphate and nitrate, i.e. are 10^{-7} to 10^{-11} cm^2 sec^{-1} and 10^{-5} to 10^{-6} cm^2 sec^{-1} respectively. It was calculated that after four days, 95 % of the P taken up by a root came from the soil solution within 0.1 mm of its surface (Blair et al., 1976). Thus, the rate of diffusion sets a limit to the zone of soil which can contribute P to the root, but within that small zone extensive removal of the labile P may well occur (Sutton & Gunary, 1969). Diffusion occurs when ions move to roots along concentration gradients, from higher concentrations to lower ones (Jones, 1982; Olsen et al., 1985; Havlin et al., 1999; Anon, s.a.). Most of the P and K move to the root by diffusion (Jones, 1982; Havlin et al., 1999) and therefore influences the relative importance of soil solution concentration on plant production (Blair et al., 1976). As plant roots absorb nutrients from the surrounding soil solution, the nutrient concentration at the root surface decreases compared with the bulk of the soil solution concentration. Therefore, a nutrient concentration gradient is established that causes ions to diffuse toward the plant root. A high plant requirement for a nutrient results in a large concentration gradient, favouring a high rate of ion diffusion from the soil solution to the root surface (Mengel & Kirby, 1987; Havlin et al., 1999). Diffusion coefficients of ions in the soil are dependant on a number of factors of which soil moisture is the most important. The other factors are the mobility of ions along adsorbing surfaces, the total concentration of ions in the soil system, concentration of ions in the soil solution and the fraction of the soil volume occupied by solution giving the cross section for diffusion (Mengel & Kirby, 1987). Because of the above mentioned, localized placement for most soils favours the uptake of P, which is dependent on diffusion and which is very reactive with soil substances that reduce its availability to plants (Jones, 1982). The very high P concentrations that exist temporarily in and near fertilizer bands are expected to encourage further P uptake by mass flow, as well as P diffusion. For example, P concentrations between 2 and 14 mg kg^{-1} have been found to occur in soil-fertilized reaction zones (Havlin et al., 1999). Soil related factors that influence P uptake, utilization and efficiency are soil type, texture and mineralogical characteristics, the organic matter content, soil temperature, soil water content, the presence of various macro and micro nutrients, the quantity of P in the soil, as well as pH and high Al concentrations. The type of fertilizer used during fertilization also influences P uptake and utilization (El Kholi, 1961; Goodman, 1969; Newbould, 1969; Sutton & Gunary, 1969; Blair et al., 1976; Bidwell, 1979; Jones, 1982; Radjagukuk, 1982; Beaton et al., 1985; Fried & Shapiro, 1985; Grunes & Allaway, 1985; Kamprath & Foy, 1985; Miller, Mamaril & Blair, 1985; Nye, 1985; Randall et al., 1985; Riley & Barber, 1985; Young et al., 1985; Blair et al., 1990; Garrity et al., 1990; Goswami et al., 1990; Parnes, 1990; Simpson, 1991; Farina et al., 1993; Havlin et al., 1999; Anon, s.a.). Plant related factors are plant type and cultivar and the root system (Blair et al., 1976; Jones, 1982; Ramirez, 1982; Randall et al., 1985; Goswami et al., 1990). The fertilizer application method, i.e. broadcasting or band-placement (Goswami et al., 1990) as well as microbiological activity, i.e. presence of *Mycorrhiza* and *Fungi* (Blair et al., 1976; Mengel & Kirby, 1987; Garrity et al., 1990) also influence P uptake and utilization.

2.4.5 Movement and translocation of phosphorus within plants

The interaction between the environmental conditions of the plant as a whole and the biochemical mechanisms involved in utilization of P is complex (Loughman, 1969). After absorption, the P in plant cells rapidly becomes involved in metabolic processes (Mengel & Kirby, 1987). Relatively high concentrations of P also accumulate in root tips, followed by a zone of lesser accumulation, where cells are elongating, and then by a second region of higher concentration, where the root hairs are developed (Havlin et al., 1999). As P is readily mobile in the plant it can be translocated in an upward or downward direction (Mengel & Kirby, 1987) and as the plant matures, much of the P is translocated from other parts into the seeds and fruits. As deficiencies develop, P moves from older tissue into younger tissue (Young et al., 1985). During an experiment with barley plants, it was found that P was taken up by basal root segments and was translocated to the root tips as well as to the upper plant parts. Young leaves are supplied not only by P taken up by the roots, but also with P originating from the older leaves. During another experiment with buckwheat in a culture solution, P was translocated initially to the younger leaves, where-after some days, retranslocation occurred and the P was partially transported to the older leaves. This downward movement occurs mainly in the phloem where phosphorylcholine is the main P carrier (Mengel & Kirby, 1987). Soil related factors, i.e. Ca and sugar content, as well as lack of oxygen will influence P movement in plants. The presence or absence of light complicates P transport. In dark conditions, P will still be absorbed at similar rates as in light conditions, but transport occurs more slowly in the dark (Loughman, 1969; Bidwell, 1979).

2.5 Phosphorus recommendations for crops

2.5.1 Determination of phosphorus levels in soils and plants

The determination of available soil P is complicated, as P of varying availability is present in the soil (Mengel & Kirby, 1987). Soil properties such as texture, organic matter content, clay types in the clay fraction and their ability and abundance, and the P sorption capacity, influence P extractability (Price, 1976). Thus, one test does not suit all situations or soil types and the choice of a suitable method for the determination of available P in a given soil depends on which P forms are dominant in the soil (Terman, 1976). By using a specific extraction method, an attempt is being made to extract from the soil a fraction of the total amount of the nutrient which is closely correlated to that actually used by plants in the field. The selection of suitable methods of analysis is difficult, because of the wide range of substances in the soil and the variation in field performances (Simpson, 1991) and the fact that there is great diversity in extraction techniques for available P among soil-testing laboratories (Jones, 1982). However, most extraction methods estimate the quantity of P in the soil solution and the readily available pool (Johnston, 2000). In acid and neutral soils a wide range of extractants has been used. These include the Bray method (NH_4F + HCl, pH 3.5), Truog method ($(NH_4)_2SO_4 + H_2SO_4$, pH 3.0) and the Ca lactate method (pH 3.7). Such acid extractants are unsuitable for apatite containing soils as they react with apatite. This is the case with calcareous soils or soils fertilized with apatitic P. For such soils the Olsen method ($NaHCO_3$, pH 8.5), Morgan method (Na acetate + acetic acid, pH 4.8) or the CAL method (Ca lactate + Ca acetate + acetic acid, pH 4.1) are more suitable. Extractants with a relatively high pH (pH > 4) are especially effective in bringing about the release of adsorbed P. The extraction of soil P by water has also been proved a useful tool in determining available soil P. Another approach to assess plant available soil P status has been to extract P from soil using synthetic anion exchange resins and results obtained have often correlated quite well with plant P uptake (Mengel & Kirby, 1987). According to Sutton & Gunary (1969) and Johnston

(2000) it is possible to predict the P supply of a soil by the amount of extractable P by anion exchange resin. Since this resin removes phosphate ions from the solution phase, but relies on desorption of P from the solid phase for the bulk of its supply, as the plant does, it is not surprising that it can account for about 70 % of the variation in uptake. In most countries, however the chosen methods adequately characterise soils in relation to their responsiveness to applications of P fertilizer. For example, in England and Wales, the Olsen method is widely used to determine readily available P (Johnston, 2000).

Plant analysis is most useful in confirming the cause of visual deficiency symptoms, especially of trace elements in crops and particularly if samples from both healthy plants and those showing symptoms can be compared (Simpson, 1991). However care should be taken with the interpretation of leaf P content to distinguish between actual deficiencies and interactions with other nutritional factors, i.e. low P leaf concentrations may be due to high acid saturation levels in the soil rather than due to a low P status (Farina et al., 1993).

2.5.2 Crop response to plant available phosphorus in soils

The amount of fertilizer P required to increase extractable soil P concentration, is dependant on several soil factors which include Al and Fe hydrous oxides, the type and amount of clay, reactive $CaCO_3$ and organic matter (Indiati, Neri, Sharpley & Fernandes, 1999). According to Locke & Hanson (1991) calibration of field crops response to nutrient availability is the basis for making fertilizer recommendations from soil tests. Thus, reliable soil P tests constitute an important step in developing more accurate fertilizer recommendations. By use of appropriate soil P tests, it is possible to determine fertilizer P requirements to reach and maintain optimal soil P levels for crop production goals. To reliably achieve this goal, it is essential to account for three parameters, i.e. the effective available soil P, the P sufficiency level that is the critical level of available soil P required for near maximum yields, and the soil P availability index, which accounts for the proportion of added P that remains available for plant uptake (Indiati et al., 1999). Furthermore, site-specific farming aiming at maximum resource efficiency has become a key issue for farmers as applying site-specific strategies will essentially contribute to long term sustainability (Pedersen, Grandzinski & Schröder, 1999). However, Rorison (1969) expressed the concern that nutritional experiments in glasshouses should be complementary to that of field experiments to verify each other. Goswami et al. (1990) stressed the fact that the crop requirement of added fertilizer should take the soil P supply and its contribution, and the efficiency of P fertilizer in a given soil-climate environment, into account. For example, for a similar yield response of wheat to P, 53 kg P ha^{-1} would be required on a high P-fixing soil as against 26 kg P ha^{-1} on a low P-fixing soil. On another soil, in order to obtain a yield response of 1 t ha^{-1}, 18 kg P ha^{-1} was required on a soil having 15 kg available P ha^{-1} (Olsen), as against 35 kg P ha^{-1} on a soil with 7.5 kg available P ha^{-1} (Olsen). In West Sumatra, maximum yields of maize were not reached until well over 88 kg P ha^{-1} was applied. Thus, many soils after a long history of fertilization become high in available P, so that neither yield response to current P application nor differences among sources can be measured, therefore the efficiency of applied P is near zero (Terman, 1976). The relationship between crop yield and P application rates at different soil P levels are illustrated in Figure 2.5.

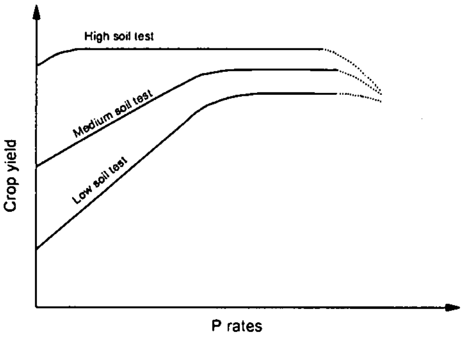


Figure 2.5 : Relationship between crop yield and P application rates at different soil P levels (Reconstructed from Terman, 1976).

According to Farina et al. (1993) optimum P soil test values increase with increasing sample density, thus the amount of fertilizer required to increase soil test by a single unit is also related to the sample density. Therefore, in making a P recommendation, both relationships are used. However, P does not build-up as rapidly in highly weathered clays and clay loams due to fixation, and long-term requirements are thus considerably higher than they are on sandy soils. It is widely assumed that the P requirement, like the N requirement, is directly related to yield potential. In other words, that where the yield potential is lower, the P requirement will also be lower. Research results in KwaZulu-Natal do not support this view, and thus the P requirement is not adjusted according to estimates of the yield potential. A certain quantity of P is required to realize potential (maximum yield), whether the potential is 3 or 7 t ha^{-1}. Lower rates of P, which might reduce 7 t ha^{-1} potential to say 5 t ha^{-1}, will also reduce a 3 t ha^{-1} to about 2 t ha^{-1}. The marked differences brought about by sample density, are due to the fact that the P soil tests do not reflect all the P present. In clay soils, a lower percentage is removed by the test than is the case in sandy soils.

Typical production functions for plant nutrients on fertile soils therefore result in comparatively flat curves (Figure 2.6). Yields achieved at zero input often are 60 % of the optimum yield or more and reducing the fertilizer rate by 10 to 20 % below the optimum rate seems to have little influence on the yield. Since this implies that the efficiency of the fertilizer is low at higher rates, environmentalists tend to press for sub-optimal rates (Kummer & Zerulla, 1999).

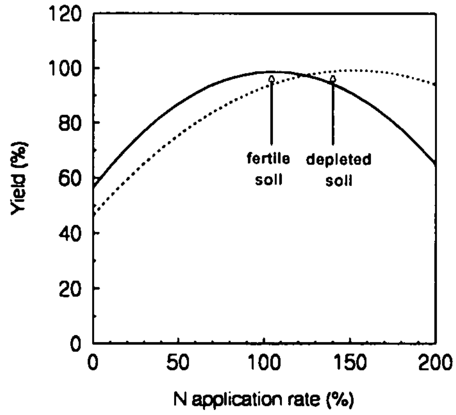


Figure 2.6 : Production functions for N on a fertile and a depleted soil (Reconstructed from Kummer & Zerulla, 1999).

Mengel & Kirby (1987) suggested that if the quantity of available soil P is in a normal range, the rate of P application required should correspond to the amount of P removed by the crop. As some of the labile P is rendered immobile, P application rates should be about 10 to 50 % higher than the quantity of P taken up by the crop. The rates generally applied to arable crops range from 20 to 80 kg P ha^{-1} according to crop species and soil conditions. Crops with a high growth rate, like maize, producing large quantities of biomass and hence have a higher demand. According to Parnes (1990) when planning to use a soluble P fertilizer, and wanting to determine the amount of P needed for the growing crop, increase the planned amount of fertilizer P by 50 %.

Several authors have attempted to relate soil properties to the effectiveness of plant recovery of fertilizer P in soil by plants. Moorehead & McLean (1985) using a quick-test method of adding P to soil, showed that P extracted after a 2-hour equilibration period closely correlated with that obtained after a two month equilibration in both laboratory and field conditions. From the 2-hour equilibration, the authors were able to estimate the amounts of fertilizer P needed to reach the optimal soil solution P concentration for crop production. In another study by Indiati, Izza & Figliolia (1991), in order to assess the suitability of soil incubation and P availability to provide reliable fertilizer P recommendations, the amounts of P required to reach a certain level of Olsen available P in soil, calculated at various soil P equilibration periods, i.e. 2, 24, 48 hours and 60 days, were compared. The results of this study showed that the amounts of P extracted after 48 hours and also after 60 days equilibrations provided fertilizer availability values (F-values, viz. fractions of added P that was available after incubation). However, it was found that more information is needed on the relationship between soil P adsorption properties and P extractability. In an incubation study Johnston, Miles and Thibaud (1991) used clay content to predict the quantity of P fertilizer needed to raise soil test P in a variety of soils. Moughli, Westfall & Boukhial (1993) included a soil PBC parameter with extractable P levels to improve the accuracy of fertilizer P recommendations for Mediterranean soils. Cox (1994) determined the effect of applied P on extractable P with time on Ultisols varying in clay content in field experiments and calculated the change in soil test P per unit of added P as a function of clay content. Indiati & Sharpley (1995) investigated the reliability of soil physical and chemical characteristics in predicting relative changes in soil P availability, P sorption, and release in simulated runoff experiments. It was found that the P sorption index (PSI) gave the best estimate of the potential change in soil P availability. Indiati et al. (1999) conducted a study on 28 representative Portuguese soils widely ranging in soil properties. The objectives of the study were to verify soil P extractability according to several conventional extractants (Olsen, Mehlich 3, and Egner) and P sink (Fe-oxide coated paper strips) after 2 hours, 24 hours and 90 days of soil P equilibration, and secondly to investigate the relationship between the determined P availability index (F-values) and soil PSI. The achieved results confirmed the suitability of the 2 hour as well as the 24 hour short-term soil P equilibration procedures for accurately predicting the actual F-values as based on longer equilibration (90 days) after "adjustment" of the data by regression analysis. The quick test recovery measurements of soil extractable P as determined by conventional extractants and the sink methodology allowed the calculation of the quantity of fertilizer P required to increase the existing soil P test level to a predetermined crop sufficiency level. However, soil P extractability of added P could be conveniently extrapolated by measuring the soil PSI, a closely correlated parameter to P sorption maxima of soil, even if at a lesser degree of accuracy.

A field experiment was established in 1981 to calibrate maize yield to extractable soil P level on a Mexico silt loam soil near Columbia, Missouri. A single application of P fertilizer was surface broadcasted in 1981 at five rates, i.e. 0, 82, 163, 244 and 328 kg P ha^{-1}. No further P application was made for the duration of the study. Soybean and maize were planted on the soil during 1981 to 1983. Extractable soil P measured with Bray 1, Bray 2 and Mehlich 2 was lower in 1983 than in 1982. Curvilinear equations represented the best fit for relationships between relative grain yield and extractable soil P levels measured with all extractants. A curvilinear equation also described the relationship between grain yield and leaf P concentration. Critical leaf P concentrations in this study ranged from 0.26 to 0.33 % (Locke & Hanson, 1991). According to 13 years' data, there was no increase in yield at an extractable P level above 45 kg ha^{-1} (Mehlich diluted HCl-H_2SO_4 extraction), but only a small increase in percent of P (Thomas, 1982). Field studies were conducted in Kentucky to determine P fertilizer rates required for near maximum yield at various residual levels of available soil P. It was found (Figure 2.7) that at extractable P levels (Bray and Kurtz 1) of more than 44 kg P ha^{-1}, no further growth response from maize, soybean, alfalfa or clover was obtained (Randall et al., 1985).

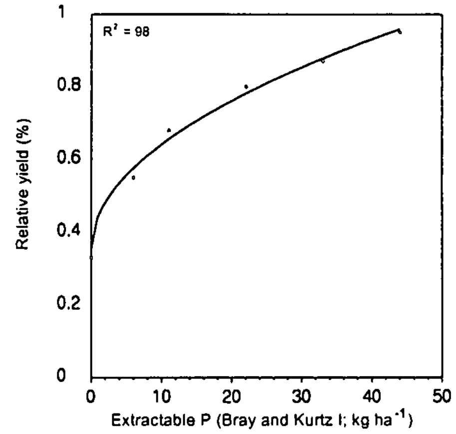


Figure 2.7 : Relationship between relative crop yield (maize, soybean, alfalfa and clover) and extractable soil P level (Reconstructed from Randall et al., 1985).

On the basis of the relationship between extractable P and relative yield, it was concluded that in order to obtain 95 % relative yield at extractable P quantities (Bray and Kurtz 1) of 0, 6, 11, 22, 33 and 44 kg P ha^{-1}, fertilizer applications of 55, 45, 37, 25, 12 and 0 kg P ha^{-1} $year^{-1}$ should be applied, respectively (Randall et al., 1985). A relationship between amounts of extractable P (Bray and Kurtz 1; kg P ha^{-1}) and fertilizer P required to obtain 95 % relative yield was also calculated. McPharlin & Robertson (1999) calculated the relationships between relative yield and P rates and between relative yield and P soil test to quantify the response of onions (*Allium cepa* L.). Sahrawat & Islam (1990) suggests 90 % relative yield for groundnut as the optimum. The amount of P necessary to obtain 90 % of maximum yield, was 7.9 mg P kg^{-1} (0.5 M $NaHCO_3$-extraction). In this study a Mitscherlich-type relation (R^2 = 83 %; Equation 2.1) between yield and extractable soil P level before planting in the top 100 mm of the soil was established.

$$\text{Kernel yield (t ha}^{-1}\text{)} = (3.1 - 4.1)^{-0.395 \,.\, \text{Extractable P}} \text{........................Equation 2.1}$$

2.5.3 Approaches used for phosphorus recommendations

2.5.3.1 World Phosphate Institute

An approach of assessing P requirements was proposed by the World Phosphate Institute (IMPHOS) in 1980, based on results of 500 soil samples, covering 13 soil groups according to the Food and Agriculture Organization of the United Nations (FAO) system, from 42 countries in tropical regions. It was suggested that soils containing less than 10 mg kg^{-1} resin-extractable P (48 hours) are P deficient. The classification system of soils was suggested with respect to their responses to P fertilizer based on physical, chemical, and biological properties and field experimental data. This classification divides soils into five groups, ranging from those with very serious deficiencies demanding first-investment fertilizer application to richer soils simply requiring maintenance fertilization. Analyses of soil texture and various P parameters (including P-fixing capacity) should be used as the basis of classification. Each group should have its own minimum critical threshold soil test value, which provides the scale of fertilizer P to be applied at the beginning of the cropping season (Cornforth, Metherell & Sorn-Scrivichai, 1990). The suggested system is summarized in Table 2.1 and the amount of P required to bring the soil to reach the critical threshold is calculated from Equation 2.2.

Table 2.1 : Classification of five soil groups by the IMPHOS concept (Cornforth et al., 1990)

Group	Deficiency level	Texture	Critical threshold* (resin P)	Constant (a)
1	Seriously deficient	Medium to fine	10 - 17	0.097
2	Medium-seriously deficient	Medium to fine	10 - 17	0.235
3	Medium-seriously deficient	Coarse	10	0.374
4	More or less deficient, high fixing capacity	Variable	23 - 33	0.351
5	Rich in P	Variable	-	-

* Qualifications where ranges of values are given depend in some instances on soil type and in others on production targets.

$$\text{P requirement (kg ha}^{-1}\text{)} = [(\text{Critical threshold value - P (48 - hour resin))}/a] \text{..............Equation 2.2}$$

Where a is a constant for each group (Table 2.1), derived from slopes of desorption isotherms of the soils studied. Although this system has been tested and found suitable for a wide range of soil types, it relies on a number of generalized assumptions that may reduce the accuracy with which fertilizer requirements are assessed for individual soil types. Improvements in this approach could result from incorporating the varying external P requirements of different crop species (Cornforth et al., 1990).

Originally, critical threshold values were those required for the highest possible yields of crops for a given time and a given soil. However this is not always applicable to tropical soils with serious P deficiencies. The IMPHOS method was proposed on the basis that the initial correction improves yield significantly without necessarily attaining the maximum possible yield to take socio-economic conditions into consideration. A figure of 60 % of maximum possible yield is used because the relationship between yield and fertilizer P application production return and fertilizer cost is therefore constant (Cornforth et al., 1990).

2.5.3.2 International Fertilizer Industry Association

According to Johnston (2000) ideally fertilizer recommendations are based on the results of field experiments in which yield is measured at increasing amounts of P applied. From the response curve relating yield to P applied, the optimum application of P is determined. In field experiments, instead of relating yield to increasing amounts of added P in fertilizer, yield is related to levels of readily available P in soils (Figure 2.8). If all factors affecting growth are optimum except readily available P, then as this factor increases, yield will increase rapidly at first, then move slowly until a plateau yield is reached. The value of readily available P at which yield closely approaches the plateau yield can be considered the critical P level for that crop and soil.

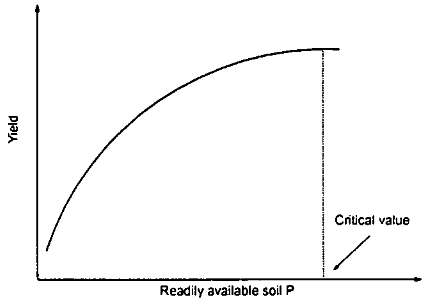


Figure 2.8 : Schematic representation of the relationship between crop yield and readily available P in soil (Reconstructed from Johnston, 2000).

Data from three field experiments were used to determine relationships between yield of potatoes, spring barley and winter wheat and extractable Olsen P. In each experiment, although there were large differences in the asymptote yield, the critical soil P value was very similar. The yield of potatoes and of spring barley differed between years due to differences in rainfall. Although applying different amounts of N to winter wheat, consequently different maximum yields were measured, but the optimum Olsen P value was independent of the final grain yield. The rationale of P fertilization should be to build up and then to maintain soils just above the critical value. At this level the simplest fertilizer recommendation will be to replace the P removed from the field in the harvested crop. The concept of replacement or maintenance applications of P fertilizers is becoming established (Johnston, 2000).

2.5.3.3 New Zealand

In New Zealand a reasonably well-defined pattern in the relationship between soil test values and the relative production of pasture has been defined (Cornforth et al., 1990). At low test values, relative yields varied from 40 to 100 %, due to the influence of climatic factors on responses to fertilizer P. As soil P status increased, the range of relative yields became narrower. They defined the "probable minimum yield" as the value below which the actual relative yield will fall on only 20 % of observations at a given soil test value. The frequency with which observed yields fall below the "probable minimum yield" can be changed if a greater or smaller risk factor seems appropriate. This approach to soil test calibration is used to derive short-term corrective fertilizer requirements. A continuous function is used to modify fertilizer recommendations calculated to replace P losses. If the soil test value is above or below the value appropriate to the production required, a modifying factor is used to respectively decrease or increase the calculated maintenance requirement. This will decrease or increase soil P status and bring it closer to the appropriate value. A typical response curve for two different soils, one with a low clay content and the other with a higher clay content is indicated in Figure 2.9. The relationship between yield and P applications forms part of the New Zealand Soil Fertility Service for P recommendations. The curvature of the response function is derived from soil texture. The curves demonstrate the difference in P requirements of two different textured soils in order to obtain the same yield (Cornforth et al., 1990).

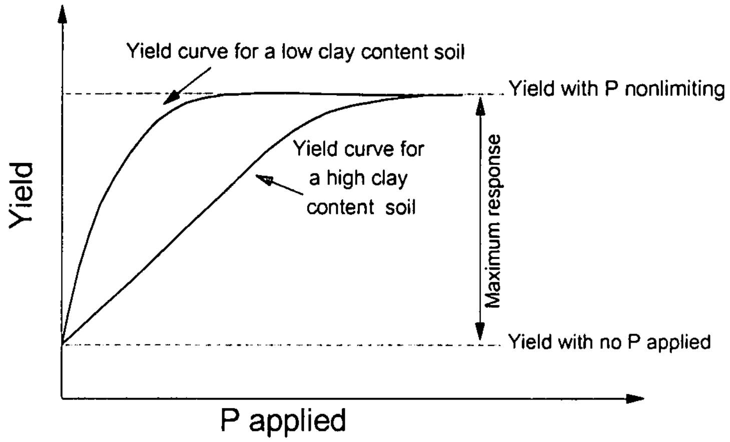


Figure 2.9 : A typical response curve for two different soils, one with a low clay content and the other with a higher clay content (Reconstructed from Cornforth et al., 1990).

2.5.3.4 Western Australia

In order to calculate the amount of P fertilizer to apply to the next crop, three steps should be taken. Firstly the relationship between yield and the level of applied P for a defined soil, environment and enterprise should be defined (Figure 2.10). The yield response curve differs for different soils and is largely affected by the capacity of adsorbed P (Bolland, 1998).

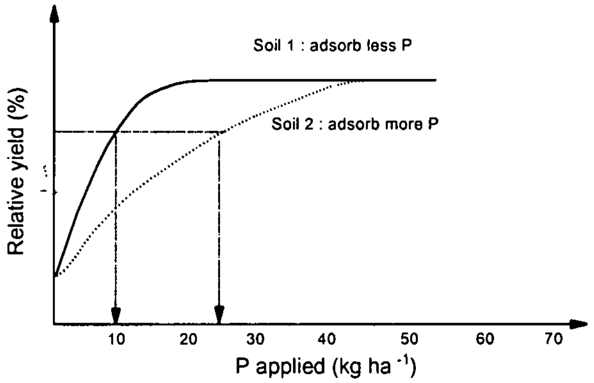


Figure 2.10 : Yield response curve to applied P of two soils with different adsorption capacities (Reconstructed from Bolland, 1998).

Secondly, the yield with the current soil P status should be determined. To do this it is necessary to define the relationship between yield and the concentration of P in the soil, i.e. the soil test calibration (Figure 2.11). The calibrations should be determined for particular soil types, environments and enterprises as for the yield response curves. Soil samples should be collected in summer and the concentration of P in the soil is related to plant yields measured later that year (Bolland, 1998).

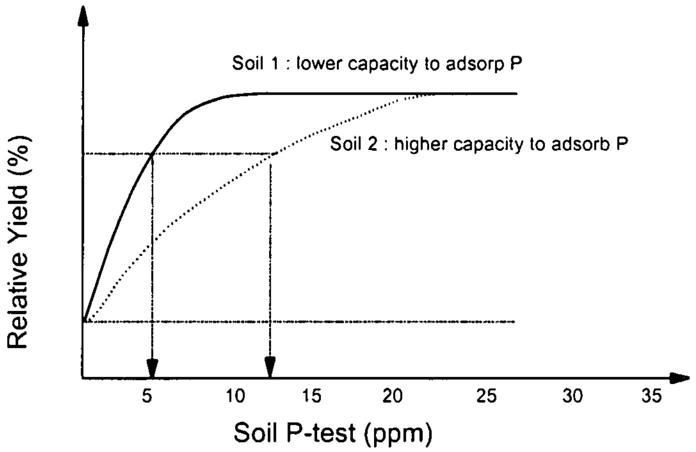


Figure 2.11 : The soil test P calibration curves for two soils with differing abilities to adsorb P (Reconstructed from Bolland, 1998).

Thirdly, the soil test calibration curve (Figure 2.11) is used to estimate the percentage of the maximum yield (relative yield) produced by the amount of P already present in the soil. This yield is then transferred to the appropriate yield response curve (Figure 2.10). It is then possible to assess the likelihood of obtaining a yield response to freshly applied P fertilizer. If the test suggests that without additional P fertilizer, the yield will be only 10 % of the potential, then there is a very high likelihood of a yield response. On the other hand, if the soil test value suggests that the soil P will produce yields approaching the maximum, then there is a very low chance of obtaining a yield response to extra fertilizer. It is important to take note that the soil test calibrations differ between years and different fertilizer types and plant species. Therefore soil test calibrations for P only provide a crude estimate of the current P status of soils. However, there is no suitable alternative to soil testing, because alternative methods require more complex experiments which are costly. The capacity of the soil to sorb P greatly influences both the yield response and soil test calibration curves. For the yield response curve, as the capacity of the soil to sorb P increases, so more fertilizer needs to be applied to produce the same yield. For the soil test calibration, as the capacity of the soil to sorb P increases, a higher concentration of P in the soil is required to produce the same yield (Bolland, 1998). However, this is in contrast with the findings of Farina et al. (1993) as discussed in Section 2.5.2.

The Ozanne & Shaw (1967) procedure is used to study P sorption by soils. The amount sorbed is the difference between the initial amount added and the concentration remaining in the equilibrium solution. The relationship between the amount of P adsorbed by the soil and the concentration in the equilibrium solution is then plotted, i.e. a P sorption isotherm (Figure 2.12) from which the following two values are determined. Firstly, when the equilibrium solution contains 0.3 $\mu g\ P\ ml^{-1}$, the amount of P sorbed by the soil is called the P adsorption (Figure 2.12). A concentration of 0.3 $\mu g\ P\ ml^{-1}$ was selected from research, because this concentration of P in the soil solution is believed to be non-limiting for pasture production in Western Australia. Secondly, the amounts of P sorbed by the soil when the concentration of P in the equilibrium solution is raised from 0.25 to 0.35 $\mu g\ P\ ml^{-1}$. The difference between these amounts is called the PBC of the soil (Bolland, 1998).

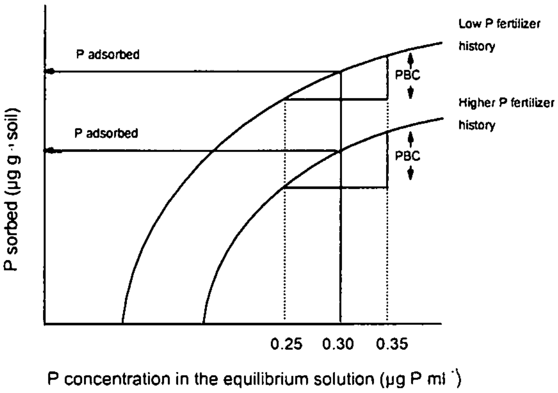


Figure 2.12 : Phosphorus sorption isotherm, showing how phosphorus buffer capacity (PBC) and P adsorption are derived (Reconstructed from Bolland, 1998).

According to Bolland (1998) the PBC is not a straight forward measure, so two others methods, the reactive Fe and P retention index (PRI) are used. Reactive Fe is the amount of Fe extracted from the soil by ammonium oxalate as described by Schwertmann (1964) and McKeague & Day (1966). The PRI can be determined by the process described by Allen & Jeffery (1990).

2.5.3.5 South Africa

Previous P guidelines for dryland maize production were based on yield target as well as soil analysis (MVSA, 1997). Then from a study by Human & Van Biljon (1994) using all available research data, a relationship between Bray 1 extractable P and relative yield was established (Figure 2.13).

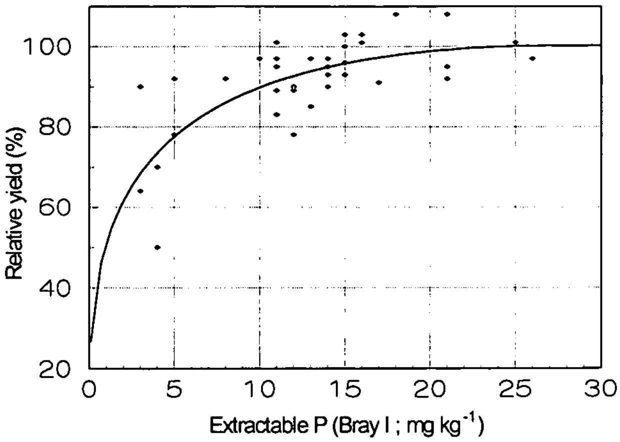


Figure 2.13 : Relationship between extractable P (Bray 1; mg kg^{-1}) and relative yield over all soils west of the Drakensberg mountains (Reconstructed from Human & Van Biljon, 1994).

The current South African P fertilizer guidelines for dryland maize production west of the Drakensberg mountains were derived from this relationship. Current P guidelines are therefore based only on soil analysis. An optimum P soil test of 17 ± 2 mg kg^{-1} (Bray 1) was derived from this relationship at 95 % relative yield which was considered to be near the economic optimum. Phosphorus requirement factors (PRF's) of 5, 7 and 9, for three different soil texture classes, i.e. < 10 %, 10 to 20 % and 21 to 35 % clay content, were recommended (Human & Van Biljon, 1994; LNR-Instituut vir Graangewasse, 1994; F.G. Adriaanse, ARC-Grain Crops Institute, Potchefstroom: Personal communication). Shortcomings of this guideline are the following, (a) the relationship was established on data from soil samples collected between maize rows at varying depths and did not include the enriched zones over the rows which result from band placement and fixed row systems, (b) one relationship was determined over all soil texture classes, (c) soils with a clay content higher than 35 % were not included, (d) the relationship was not established at absolute values, but at applications of 5 to 11 kg P ha^{-1} in the band at planting and (e) the R^2-value for the relationship was only 50 %.

2.6 Conclusion

The importance of P to crop growth is well known. The basic processes of P additions and removals from the soil, as well as internal transformations and interactions are determined by physical, chemical and biological processes and can be illustrated by the P cycle. Globally, crop producers try to manage the availability of soil P in attempts to increase or optimize crop uptake of P and yields. However, for the P cycle to be in equilibrium, it is not that simple as the inorganic and organic chemistry of P compounds in soil is of great complexity. This explains the different P fertilizer guidelines and approaches by institutions and countries worldwide in order to try and quantify and manage P availability to crops. Practical control of P availability can be obtained by crop producers by the following management practices, i.e. saturation of P-fixing capacity, placement of P fertilizers, combination of ammonium and P fertilizers, choice of P-efficient plants, increased cycling of organic P, increased cycling of organic matter, control of soil pH and enhancement of mycorrhizal symbiosis. Efforts should continue to find ways of enhancing P availability, through soil testing, appropriate rates of P application, and utilization of organic or manure sources of P in an increasing number of agricultural production systems.

CHAPTER 3

CHARACTERIZATION OF EXPERIMENTAL SITES AND PROCEDURES

To determine the relationship between extractable P and maize yield as well as changes in extractable soil P, data from 14 maize fertilization trials at several localities was used. Information concerning localities as well as procedures that were followed at each, are discussed below.

3.1 Localities and geographical information

The distribution of the localities where the trials were conducted is presented in Figure 3.1. More geographical information on the localities is summarized in Table 3.1.

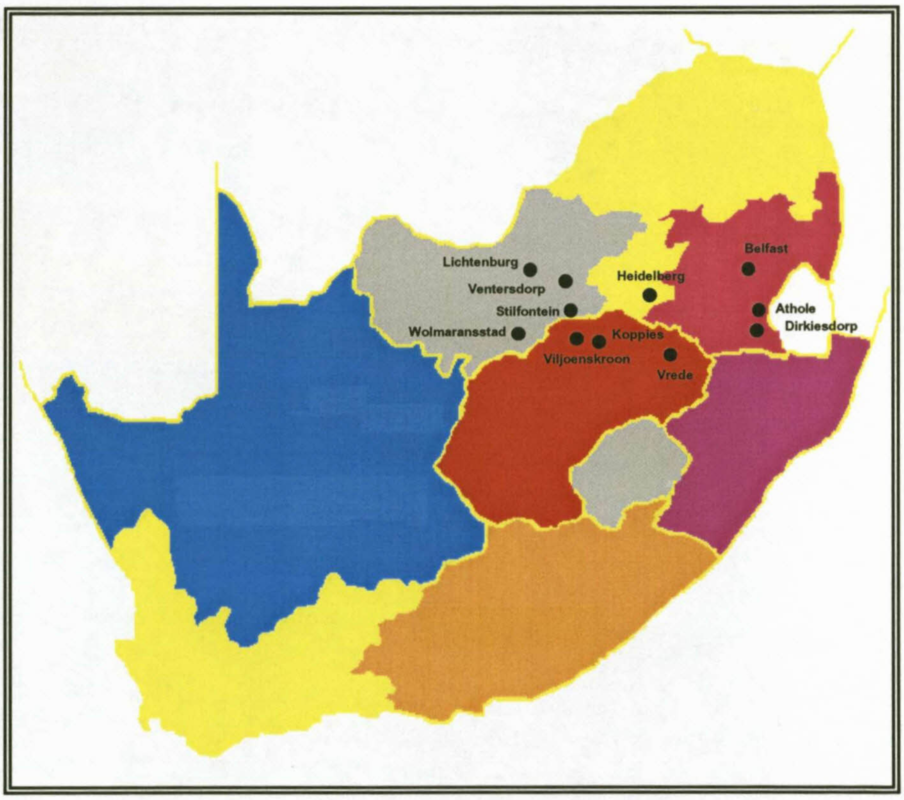


Figure 3.1 : Distribution of localities where trials were conducted.

Table 3.1 : Geographical information for all trial sites

Trial	Locality	Province	Farm	Latitude (S)	Longitude (E)	Altitude[1] (m)
1	Lichtenburg	North West	Manana	26°06.861'	26°14.760'	1447
2	Wolmaransstad	North West	Uitvalgrond	27°05.404'	26°02.532'	1377
3	Koppies (2.24 m) [2]	Free State	Susannaskuil	27°10.920'	27°37.237'	1419
4	Ventersdorp	North West	Magopa	26°06.363'	26°47.064'	1494
5	Viljoenskroon	Free State	Northleigh	27°12.159'	26°58.330'	1334
6	Stilfontein (N x P) [3]	North West	Buffeldoorns	26°43.565'	26°48.075'	1357
7	Stilfontein (P) [3]	North West	Buffeldoorns	26°43.565'	26°48.075'	1357
8	Heidelberg (N x P)	Gauteng	Wolwepan	26°42.704'	28°18.125'	1607
9	Heidelberg (Lime x P)	Gauteng	Wolwepan	26°42.205'	28°18.447'	1607
10	Athole	Mpumalanga	Research station	26°35.548'	30°29.853'	1620
11	Belfast	Mpumalanga	Leeubank	25°45.940'	29°59.041'	1970
12	Vrede	Free State	Wapad	27°32.233'	29°11.767'	1600
13	Koppies (0.90 m) [2]	Free State	Susannaskuil	27°10.920'	27°37.237'	1419
14	Dirkiesdorp	Mpumalanga	Eerste Geluk	27°07.863'	30°21.558'	1370

[1] - Approximate altitude according to weather stations, listed in Table 3.4 (ARC-ISCW, 2001; South African Weather Bureau, 2001); [2] - Two trials were conducted at Koppies, viz. at wide row width spacing of 2.24 m and at narrow row width spacing of 0.90 m; [3] - Two trials were conducted at Stilfontein, viz. N x P trial and a P source trial.

According to crop estimates during April 2001 it was expected that 38.1, 29.5 and 21.5 % of all maize yielded in South Africa would probably be produced by the Free State, North West and Mpumalanga Provinces, respectively. Of the remaining 10.9 %, 4.1 % would probably be produced by Gauteng, 2.6 % by KwaZulu-Natal, 2.5 % by Northern Cape, and the remaining 1.7 % collectively by the Western Cape, Eastern Cape and the Northern Provinces (Crop Estimates Committee, 2001). Of the 14 trials included in this study, four were conducted in the Free State Province, five in the North West Province, three in the Mpumalanga Province and two in the Gauteng Province.

Land types and reasonably homogeneous farming areas (RHFA) to which each of the localities belonged are summarized in Table 3.2. A land type is defined as an area where the macro climate, terrain form and soil pattern each show a clear degree of uniformity. This degree of uniformity is such that, agriculturally, there would be little advantages in defining further subdivisions of these landscape units on a country-wide basis. One land type differs from the other in one or more of the characteristics mentioned (Macvicar, 1974; Macvicar, Scotney, Skinner, Niehaus & Loubser, 1974; Van der Watt & Van Rooyen, 1995). A RHFA is defined as a demarcated area on a map with a specific pattern of soil suitability classes. The climatic factors within each soil suitability class will not vary sufficiently to substantially influence production practices and agriculture potential within the same land unit (Ludick & Wooding, 1991; Jordaan, 1997).

Table 3.2 : Land types and reasonably homogeneous farming areas (RHFA) that the localities belong to

Trial	Locality	Land type	Definition, geology, demarcation and climate	RHFA[1]
1	Lichtenburg[2]	Bd10n	Plinthic catena with upland duplex and margalitic soils rare and eutrophic red soils not widespread. Geology is made up by Ventersdorp and Dominion lava, where basement Complex granite occurs sporadically. Pans occupy 4 % of the land type. It occurs on A2 terrain units. Demarcated on map 2626 Wes-Rand and situated in climate zone 11S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).	6006
		Fa11c	Glenrosa and/or Mispah forms (other soils may occur) with lime rare or absent in the entire landscape. Geology is made up by dolomite and chert belonging to the Chuniespoort Group, with chert gravels abundant on middle and foot slopes including valley bottoms. It occurs on A2 terrain units. Demarcated on map 2626 Wes-Rand and situated in climate zone 11S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).	6002
2	Wolmaransstad	Bc19c	Plinthic catena with upland duplex and margalitic soils rare and eutrophic red soils widespread. Geology is made up by andesitic to basaltic lava of the Ventersdorp Supergroup with sporadic occurrence of Ventersdorp quartzite and grit. Demarcated on map 2627 Kroonstad and situated in climate zone 11S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).	6006
3	Koppies	Dc7a	Prismacutanic and/or pedocutanic diagnostic horizons dominant. In addition, one of more of vertic, melanic and/or red structured diagnostic horizons may occur. Geology is made up of Ecca shale and sandstone, with many dolerite sills. Sporadic occurrence of Basement Complex granite in the west. It occurs on A2 terrain units. Demarcated on map 2627 Kroonstad and situated in climate zone 29S (Bruce & Schoeman, 1979b; Land Type Survey Staff, 1984).	6023
4	Ventersdorp	Fa15a	Glenrosa and/or Mispah forms (other soils may occur) with lime rare or absent in the entire landscape. Geology is made up by dolomite and chert belonging to the Chuniespoort Group, with chert gravels abundant on middle and foot slopes including valley bottoms. It occurs on A2 terrain units. Demarcated on map 2626 Wes-Rand and situated in climate zone 11S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).	6002
5	Viljoenskroon	Bd14a	Plinthic catena with upland duplex and margalitic soils rare and eutrophic red soils are not spread. Geology is made up by Ecca sandstone, mudstone and shale, with occasional dolerite sills and with sporadic occurrence of Hekpoort lava, diabase and quartzite in east. Aeolian sand overlies nearly all rocks. Pans occupy 1 % of land type. It occurs on A2 terrain units. Demarcated on map 2627 Kroonstad and situated in climate zone 31S (Bruce & Schoeman, 1979b; Land Type Survey Staff, 1984).	6027

6	Stilfontein (N x P)	Ba42b	Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils are widespread. Geology is made up by Witwatersrand quartzite and shale with Ventersdorp lava and Basement Complex granite in places. It occurs on A3 terrain units. Demarcated on map 2626 West Rand and situated in climate zone 21S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).	6017
7	Stilfontein (P)	Ba42b	Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils are widespread. Geology is made up by Witwatersrand quartzite and shale with Ventersdorp lava and Basement Complex granite in places. It occurs on A3 terrain units. Demarcated on map 2626 West Rand and situated in climate zone 21S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).	6017
8	Heidelberg (N x P)	Ba30a	Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils are widespread. Geology is made up by andesitic lava of the Hekpoort Formation of the Pretoria Group - Transvaal Sequence and dolerite, sandstone, grit and shale of the Ecca Group - Karoo Sequence. It occurs on A3 terrain units. Demarcated on map 2628 East Rand and situated in climate zone 21S (Land Type Survey Staff, 1985; Schoeman & Fitzpatrick, 1985a).	6011
9	Heidelberg (Lime x P)	Ba30a	Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils are widespread. Geology is made up by andesitic lava of the Hekpoort Formation of the Pretoria Group - Transvaal Sequence and dolerite, sandstone, grit and shale of the Ecca Group - Karoo Sequence. It occurs on A3 terrain units. Demarcated on map 2628 East Rand and situated in climate zone 21S (Land Type Survey Staff, 1985; Schoeman & Fitzpatrick, 1985a).	6011
10	Athole	Ac36a	Red-yellow apedal, freely drained soils with red and yellow dystrophic and /or mesotrophic soils. Geology is made up by gabbro and ultrabasic rocks of the Usushwana Complex, shale and sandstone of the Ecca Group - Karoo Sequence and lava, pyroclasts, quartzite and schist if the Insuze Group - Pongola Sequence. It occurs on B4 terrain units. Demarcated on map 2630 Mbabane and situated in climate zone 110S (Land Type Survey Staff, 1985; Schoeman & Fitzpatrick, 1985b).	?[3]
11	Belfast	Ad1a	Red-yellow apedal, freely drained soils which may be yellow and distrophic and/or mesotrophic. Geology is made up by shale, sandstone and grit of the Ecca Group, Karoo Sequence. It occurs on A3 terrain units. Demarcated on map 2528 Pretoria and situated in climate zone 50S (Schoeman, Meldahl-Johnsen, Fitzpatrick & Verster, 1985; Land Type Survey Staff, 1987).	?[3]
12	Vrede	Ea93a	One or more of vertic, melanic and red structured diagnostic horizons with undifferentiated soils. Geology is made up by mudstone, shale, sandstone and possibly grit of the Beaufort Group - Karoo Sequence. Ecca shale, sandstone and grit in the north. Dolerite sills abundant. It occurs on B4 terrain units. Demarcated on map 2728 Frankfort and situated in climate zone 30G (Schoeman, Bruce & Turner, 1984; Land Type Survey Staff, Unpublished data[4]).	6044
13	Koppies (0.90 m)	Dc7a	Prismacutanic and/or pedocutanic diagnostic horizons dominant. In addition, one of more of vertic, melanic and/or red structured diagnostic horizons may occur. Geology is made up of Ecca shale and sandstone, with many dolerite sills. Sporadic occurrence of Basement Complex granite in the west. It occurs on A2 terrain units. Demarcated on map 2627 Kroonstad and situated in climate zone 29S (Bruce & Schoeman, 1979b; Land Type Survey Staff, 1984).	6023

14	Dirkiesdorp	Bb36b	Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils not widespread. Geology is made up by mainly sandstone of the Vryheid Formation - Ecca Group, with dolerite. Small areas of alluvium and shale of the Pietermaritzburg Formation - Ecca Group, metaquartzite and banded ironstone of the Five Tree Group. Dunite and pyroxenite also occur. It occurs on A3 terrain units. Demarcated on map 2730 Vryheid and situated in climate zone 111S (Turner, Smith-Baillie, Fitzpatrick, Plath & Vivian, 1985; Land Type Survey Staff, 1986).	?[3]

[1] - Ludick & Wooding (1991); [2] - Land type according to coordinates is Bd10n, but according to properties, the soil rather belongs to the close by Fa11c land type. See soil profile description Appendix 3.1. [3] - Information not available; [4] - Unpublished data from Land Type Survey, Map 2728 Frankfort by R.W. Bruce & J.L. Schoeman.

There is great similarity between land types and RHFA's and thus, the latter can be seen as "bigger land type units". Unfortunately the demarcation of RHFA's was not done for all farming areas of South Africa, but mostly for the Highveld region.

From the above mentioned information it is clear that localities differ mostly from each other and that only a few localities belong to the same land types, viz. Stilfontein (both trials) and Heidelberg (both trials) to the Ba land type and Lichtenburg and Viljoenskroon to the Bd land type. Climate zones also differ widely and only those of the following localities correspond, i.e. Stilfontein (both trials) and Heidelberg (both trials) in climate zone 21S, and Lichtenburg, Venterdorp and Wolmaransstad in climate zone 11S. The RHFA's in which the localities fall also differ from each other.

3.2 Long-term and seasonal rainfall

The 14 trials were conducted for various periods as shown in Table 3.3. At the time when data was processed to write this thesis all trials except those at Koppies (both trials), Ventersdorp, Viljoenskroon and Dirkiesdorp had been terminated. However, all data from the terminated trials as well as the available data from the ongoing trials was used for the purpose of this study. Therefore the long-term and seasonal rainfall for the experimental years at every locality is given.

Rainfall data from the nearest weather station (primary station) was used for comparisons, but data from other nearby stations (secondary stations) were used to complete incomplete data sets. Weather stations used for rainfall determination at the different localities are summarized in Table 3.4. The long-term and seasonal rainfall as it occurred in seven day periods between 1 October until 30 September of each growing season at the different localities, as well as the total amount of rainfall, is presented in Figures 3.2 (ARC-

ISCW, 2001; South African Weather Bureau, 2001).

Table 3.3 : Duration of trials at different localities

Trial	Locality	Duration	Number of seasons
1	Lichtenburg	1989/90 - 1997/98	9
2	Wolmaransstad	1991/92 - 1997/98	7
3	Koppies (2.24 m)	1998/99 - 2000/01	3
4	Ventersdorp	2001/02	1
5	Viljoenskroon	1993/94 - 2000/01	8
6	Stilfontein (N x P)	1998/99 - 1999/00	2
7	Stilfontein (P)	1998/99 - 1999/00	2
8	Heidelberg (N x P)	1991/92 - 1997/98	7
9	Heidelberg (Lime x P)	1991/92 - 1997/98	7
10	Athole	1996/97 - 1997/98	2
11	Belfast	1996/97	1
12	Vrede	1996/97 - 1997/98	2
13	Koppies (0.90 m)	1998/99 - 2000/01	3
14	Dirkiesdorp [1]	1996/97 - 2000/01	3

[1] - The trial was established and carried out by other researchers during the first two seasons. Unfortunately data from these two seasons is not available, therefore only data for the 1998/99 until the 2000/01 seasons has been used in the study.

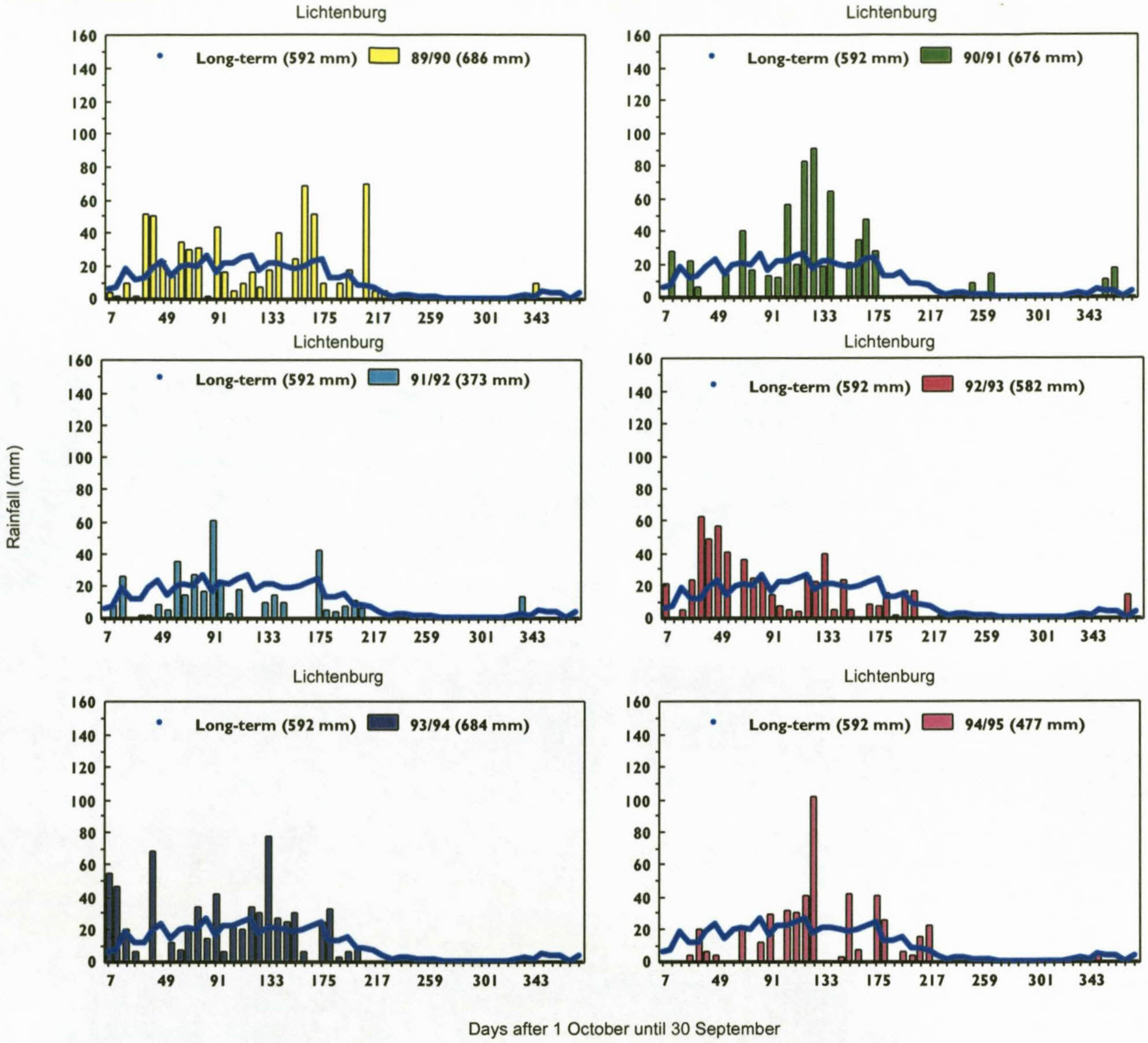
During the majority of growing seasons over all localities seasonal rainfall mainly occurred between 1 October and the end of March or April (183 or 212 days after 1 October, respectively) in accordance with the long-term rainfall pattern. However, at some localities rain occurred during winter and spring at varying amounts. The seasonal rainfall as a percentage of the long-term rainfall for every growing season at the different localities is summarized in Table 3.5.

Table 3.4 : Summary of primary (P) and secondary (S) weather stations used for the determination of long-term and seasonal rainfall at the different localities (ARC-ISCW, 2001; South African Weather Bureau, 2001)

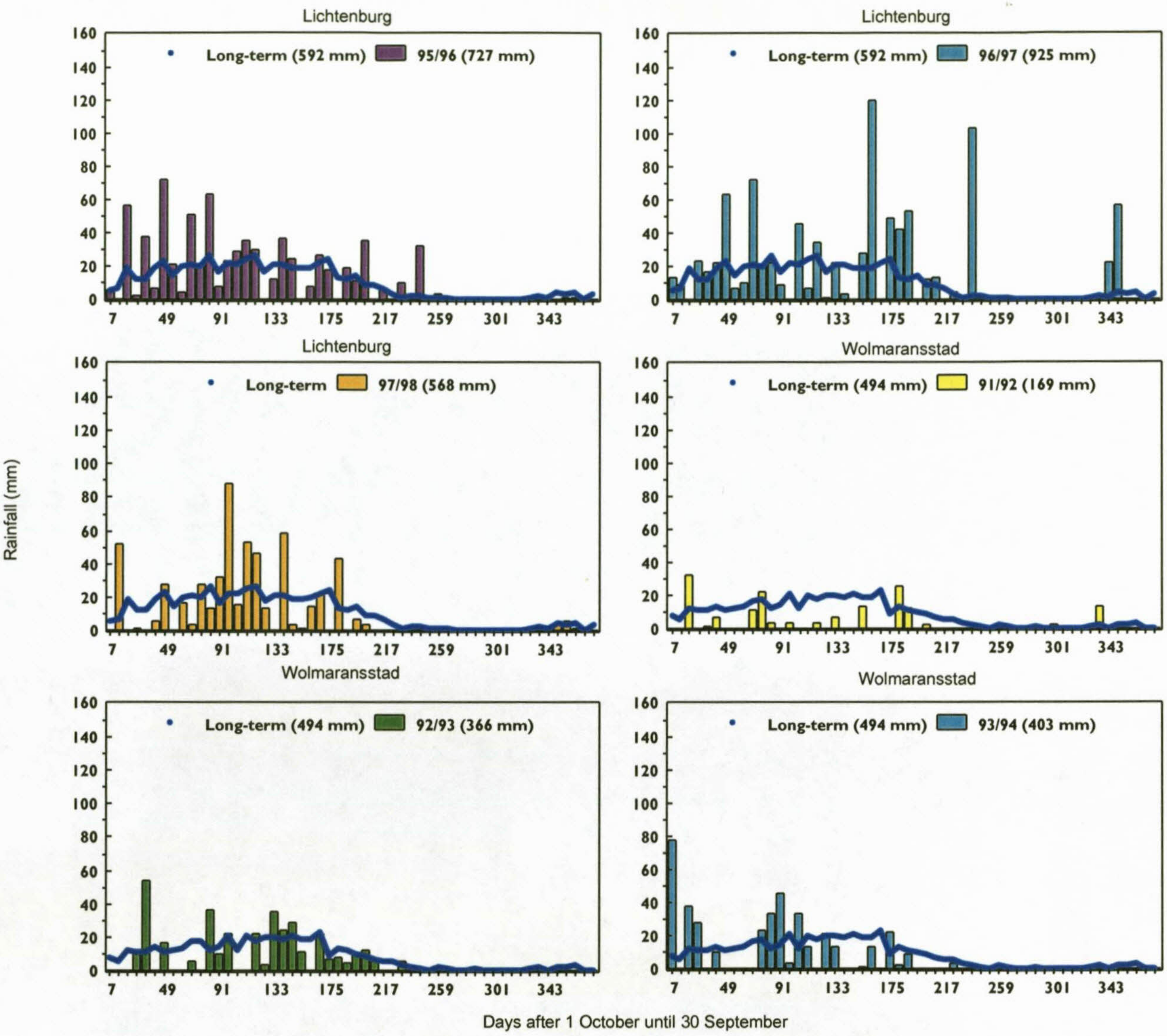
Trial	Locality	Name	Computer	Longitude	Latitude	Altitude	Period	Years
				(degree and minute)		(m)		
1	Lichtenburg	Manana (P) [1]	16450	2605	2616	1447	1954/55 - '98/99	45
		Lichtenburg (S)[1]	20396	2608	2611	?	1991, '95	2
		Lichtenburg - Sensako (S)[1]	19828	2610	2610	1477	1994	1
2	Wolmaransstad	Rietpan (P)[1]	15593	2719	2544	1325	1932/33 - '97/98	66
		Rooipoort (S)[1]	15601	2706	2600	1311	1965, '97, '90	3
		Uitkyk (S)[1]	15604	2716	2607	1329	1951	1
		Leeudoringstad (S)[1]	15608	2714	2614	1319	1990, '98, '99	3
		Vogelstruis (S)[1]	20423	2659	2549	1433	1990, '94, '98	3
		Vogelstruiskuil (S)[1]	16018	2659	2550	1433	1990, '98	2
		Strydpoort (S)[1]	20427	2659	2557	1440	1990	1
		Brakpan (S)[1]	16013	2659	2542	1417	1990, '98, '99	3
		Wolmaransstad - depot (S)[1]	20382	2711	2558	1385	1990,'94,'95,'98	4
3	Koppies (2.24 m)	Doorndraai (P)[1]	15672	2716	2736	1400	1940/41 - '98/99	58
		Koppies - depot (S)[1]	20367	2714	2733	1420	1987/88 - '98/99	12
		Rooiwal (S)[1]	20343	2717	2731	?	1988/89 - '97/98	10
		Greenlands (S)[1]	20304	2705	2743	?	1987/88 - '97/98	11
		Viljoenslaagte (S)[1]	19900	2714	2727	1401	1983/84 - '98/99	16
		Honingkloof (S)[1]	15676	2708	2743	1490	1963, '64	2
		Morgenrood (S)[1]	15667	2721	2733	1384	1993/94 - '97/98	5
		Koppies (S) [2]	0402104 0	?	?	?	1998/99 - 2000/01	3
4	Ventersdorp	Ventersdorp (P)[1]	16473	2649	2619	± 1395	1942 - 1999	57
		Ventersdorp (P)[2]	0473352 X	2622	2642	1460	2001 - 2002	1
5	Viljoenskroon	Rietpan (P)[1]	19844	2710	2655	1321	1955/56 - '98/99	44
		Viljoenskroon - Co-op (S)[1]	19836	2710	2658	1356	1978, '79	2
		Northleigh (S)[1]	19832	2712	2700	1325	1992, '97	2
		Viljoenskroon - depot (S)[1]	20353	2712	2652	?	1987, '89, '90	3
		Viljoenskroon (S)[2]	04007929	?	?	?	1999, 2000	2
6	Stilfontein (N x P)	Koekoemoer (P)[1]	20830	2651	2648	1334	1905/06 - '50/51	46
		Beatrix (P)[1]	16065	2645	2647	1372	1951/52 - '98/99	48
		Beatrix (S)[1]	16065	2645	2647	1372	1910, '26, '28, '35, '38,	7
		Faan Meintjies (S)[1]	16051	2648	2638	1350	1990, '91, '92, '94, '95,	6
		Klerksdorp - depot (S)[1]	20306	2652	2637	?	1992, '95, '99	3
7	Stilfontein (P)	Koekoemoer (P)[1]	20830	2651	2648	1334	1905/06 - '50/51	46
		Beatrix (P)[1]	16065	2645	2647	1372	1951/52 - '98/99	48
		Beatrix (S)[1]	16065	2645	2647	1372	1910, '26, '28, '35, '38,	7
		Faan Meintjies (S)[1]	16051	2648	2638	1350	1990, '91, '92, '94, '95,	6
		Klerksdorp - depot (S)[1]	20306	2652	2637	?	1992, '95, '99	3
		Klerksdorp (S)[2]	?	?	?	?	1997, '99	2
		Klerksdorp (S)[2]	?	?	?	?	1997, '99	2

8	Heidelberg (N x P)	Tamboekiesfontein (P)[1]	16658	2640	2820	1555	1963/64 - '80//81	18
		Kliprivier (P)[1]	16621	2640	2810	1497	1982/83 - '90/91	9
		Heidelberg (P)[1]	16679	2650	2840	1541	1970/71 - '91/92	22
		Schikfontein (S)[1]	16161	2660	2820	1555	1991/92 - '97/98	7
		Heidelberg (S)[1]	16684	2650	2840	1520	1990/91 - '98/99	9
		Glenroy (S)[1]	16676	2640	2830	1582	1981, '82	2
		Alberton (S)[1]	16632	2630	2810	1585	1990/91 - '98/99	9
		Meyerton (S)[1]	16152	2650	2800	1490	1990/91 - '98/99	9
		East Rand (S)[1]	16665	2620	2820	1631	1990/91 - '98/99	9
		Boksburg (S)[1]	16668	2620	2830	1631	1990/91 - '97/98	8
		Nigel (S)[1]	16700	2640	2850	1573	1990/91 - '98/99	9
		Rosherville (S)[1]	16627	2620	2810	1695	1990/91 - '97/98	8
		Springs (S)[1]	16690	2630	2840	1628	1990/91 - '97/98	8
		Turffontein (S)[1]	16590	2620	2800	1707	1990/91 - '97/98	8
9	Heidelberg (Lime x P)	Tamboekiesfontein (P)[1]	16658	2640	2820	1555	1963/64 - '80//81	18
		Kliprivier (P)[1]	16621	2640	2810	1497	1982/83 - '90/91	9
		Heidelberg (P)[1]	16679	2650	2840	1541	1970/71 - '91/92	22
		Schikfontein (S)[1]	16161	2660	2820	1555	1991/92 - '97/98	7
		Heidelberg (S)[1]	16684	2650	2840	1520	1990/91 - '98/99	9
		Glenroy (S)[1]	16676	2640	2830	1582	1981, '82	2
		Alberton (S)[1]	16632	2630	2810	1585	1990/91 - '98/99	9
		Meyerton (S)[1]	16152	2650	2800	1490	1990/91 - '98/99	9
		East Rand (S)[1]	16665	2620	2820	1631	1990/91 - '98/99	9
		Boksburg (S)[1]	16668	2620	2830	1631	1990/91 - '97/98	8
		Nigel (S)[1]	16700	2640	2850	1573	1990/91 - '98/99	9
		Rosherville (S)[1]	16627	2620	2810	1695	1990/91 - '97/98	8
		Springs (S)[1]	16690	2630	2840	1628	1990/91 - '97/98	8
		Turffontein (S)[1]	16590	2620	2800	1707	1990/91 - '97/98	8
		Olympia Park (S)[1]	16694	2630	2840	1628	1990/91 - '97/98	8
		Olympia Park (S)[1]	16694	2630	2840	1628	1990/91 - '97/98	8
10	Athole	Agricultural station (P)[1]	16301	2636	3035	1620	1970/71 - '97/98	28
11	Belfast	Belfast Police (P)[1]	17384	2542	3003	1970	1963/64 - '97/98	35
12	Vrede	Vrede - Co-op (P)[1]	15752	2725	2910	1600	1918/19 - '97/98	80
13	Koppies (0.90 m)	Doorndraai (P)[1]	15672	2716	2736	1400	1940/41 - '98/99	58
		Koppies - depot (S)[1]	20367	2714	2733	1420	1987/88 - '98/99	12
		Rooiwal (S)[1]	20343	2717	2731	?	1988/89 - '97/98	10
		Greenlands (S)[1]	20304	2705	2743	?	1987/88 - '97/98	11
		Viljoenslaagte (S)[1]	19900	2714	2727	1401	1983/84 - '98/99	16
		Honingkloof (S)[1]	15676	2708	2743	1490	1963, '64	2
		Morgenrood (S)[1]	15667	2721	2733	1384	1993/94 - '97/98	5
		Koppies (S)[2]	0402104 0	?	?	?	1998/99 - 2000/01	3
14	Dirkiesdorp	Dirkiesdorp - Police (P)[1]	15811	2710	3025	1370	1967/68 - '98/99	32
		Commondale (S)[1]	15830	2714	3054	1040	1990, '94, '99	3
		Groot Rietvlei (S)[1]	15810	2709	3022	1372	1975, '92, '93	3
		Piet Retief (S)[1]	20967	2700	3049	1236	1990	1
		Piet Retief - Co-op (S)[1]	16316	2700	3048	1236	1990	1
		Dirkiesdorp Police (P)[2]	0407730 6	2710	3025	1370	1998/99 - 2000/01	3

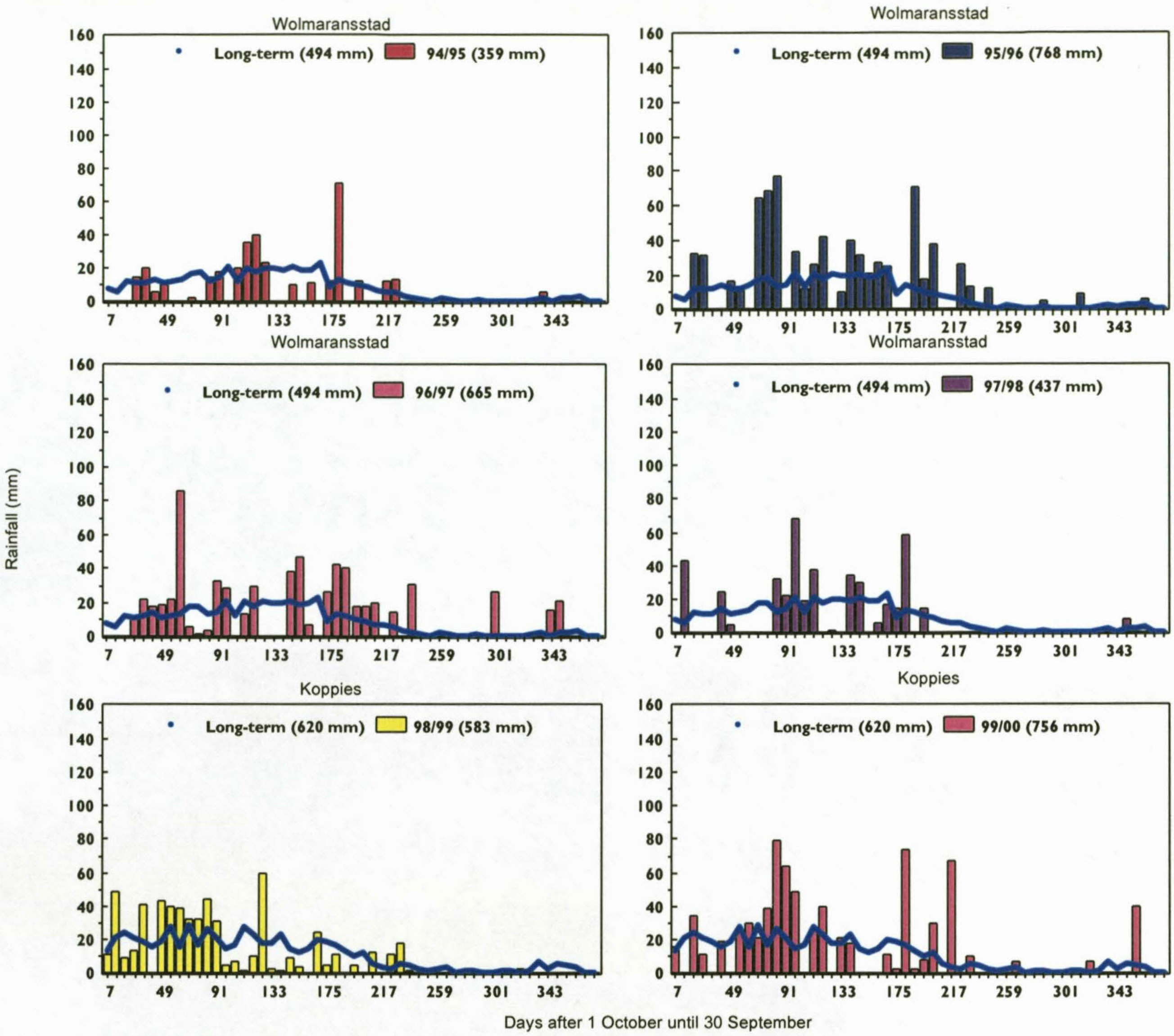
[1] - ARC-ISCW (2001) [2] - South African Weather Bureau (2001)



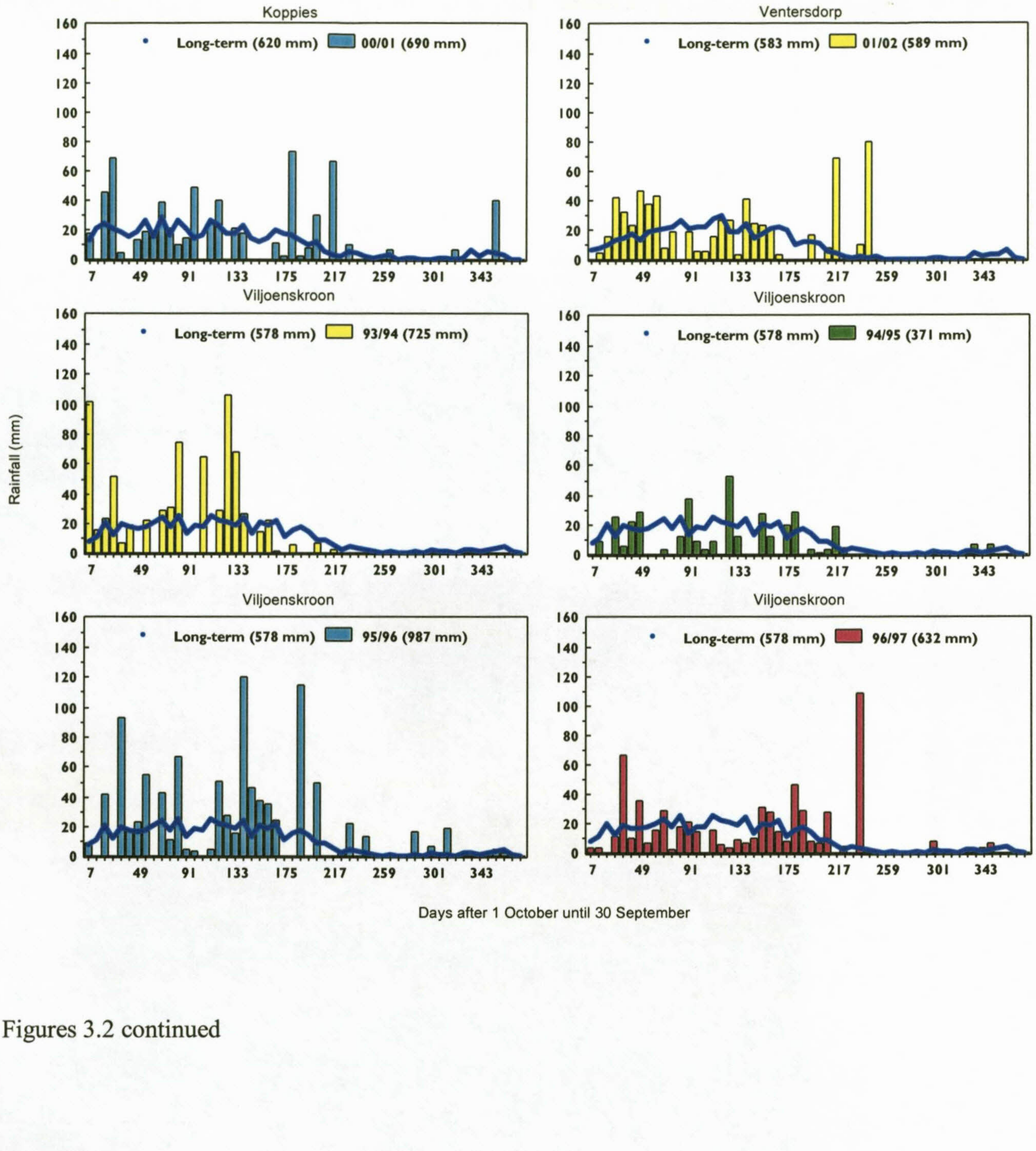
Figures 3.2 : Long-term and seasonal rainfall as it occurred in 7 day periods between 1 October until 30 September of each growing season at the different localities with the totals in brackets.



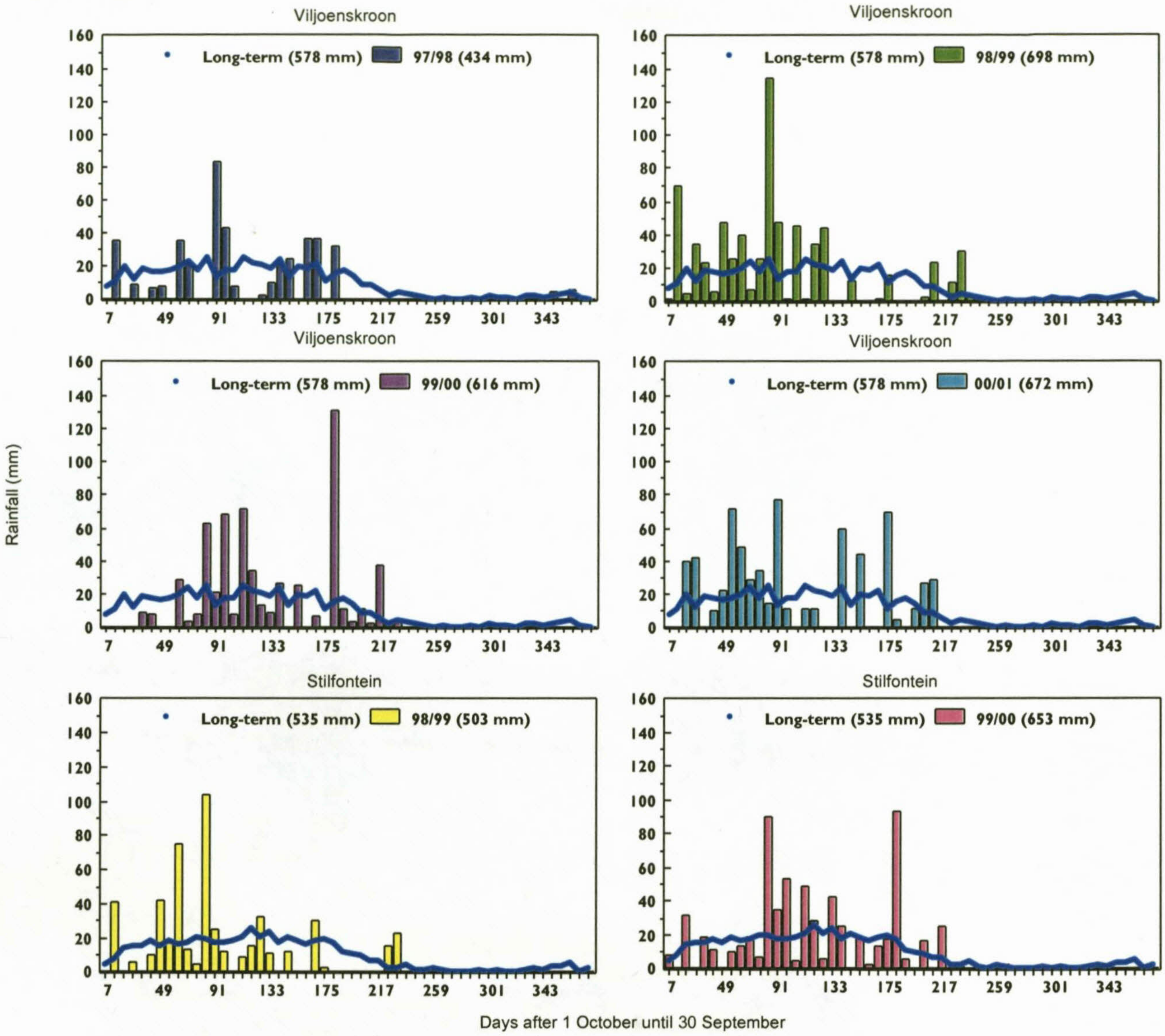
Figures 3.2 continued



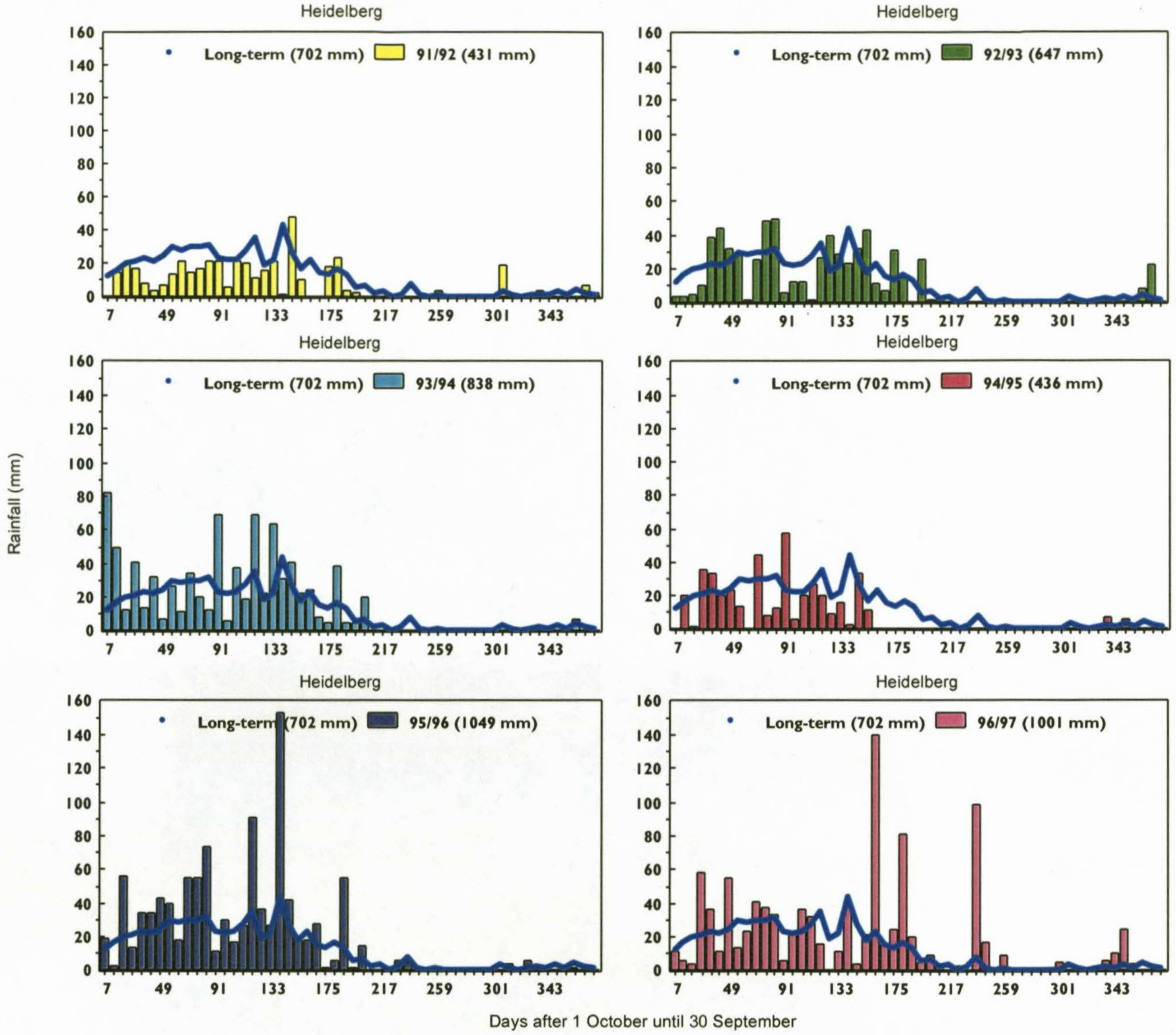
Figures 3.2 continued



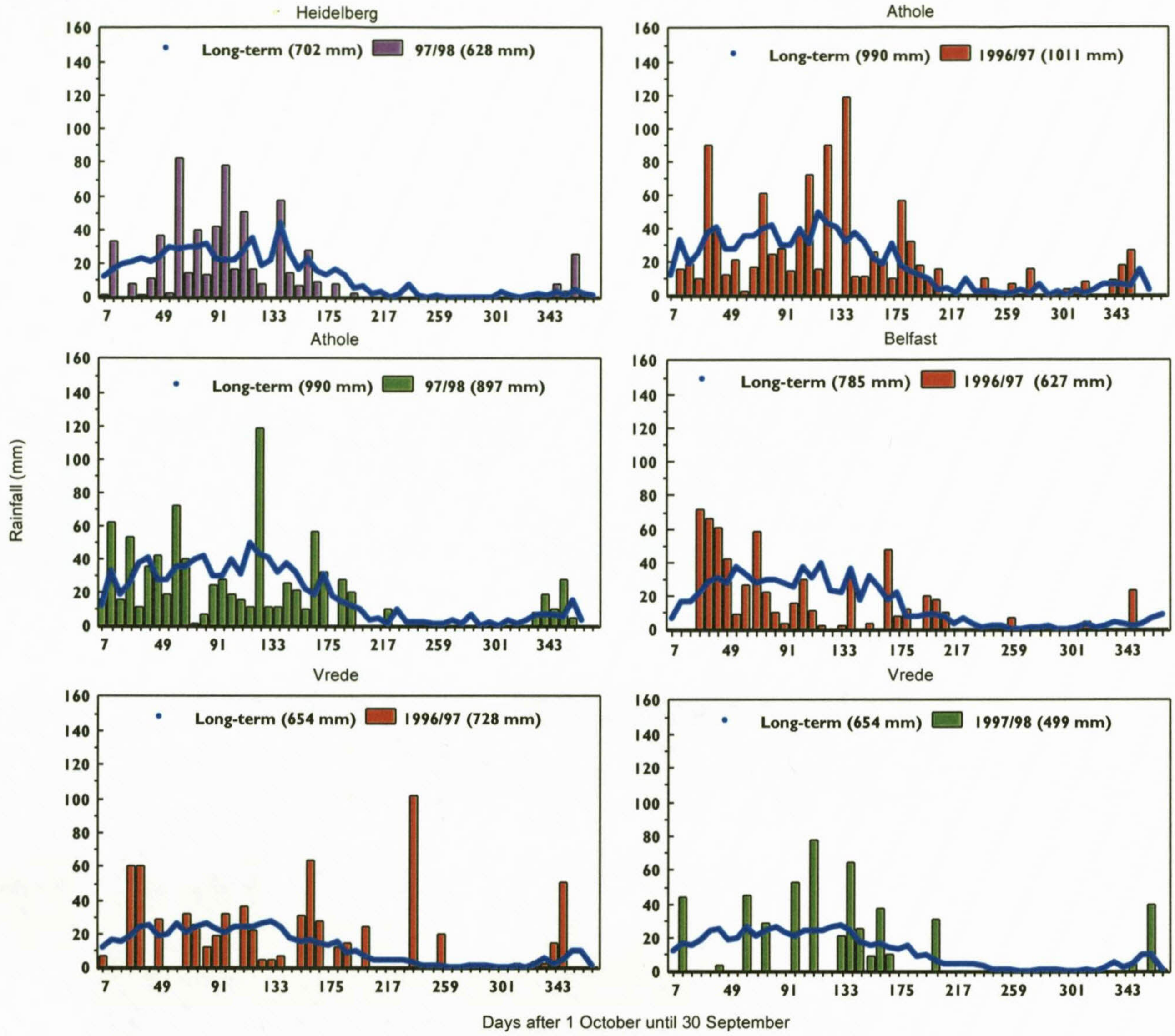
Figures 3.2 continued



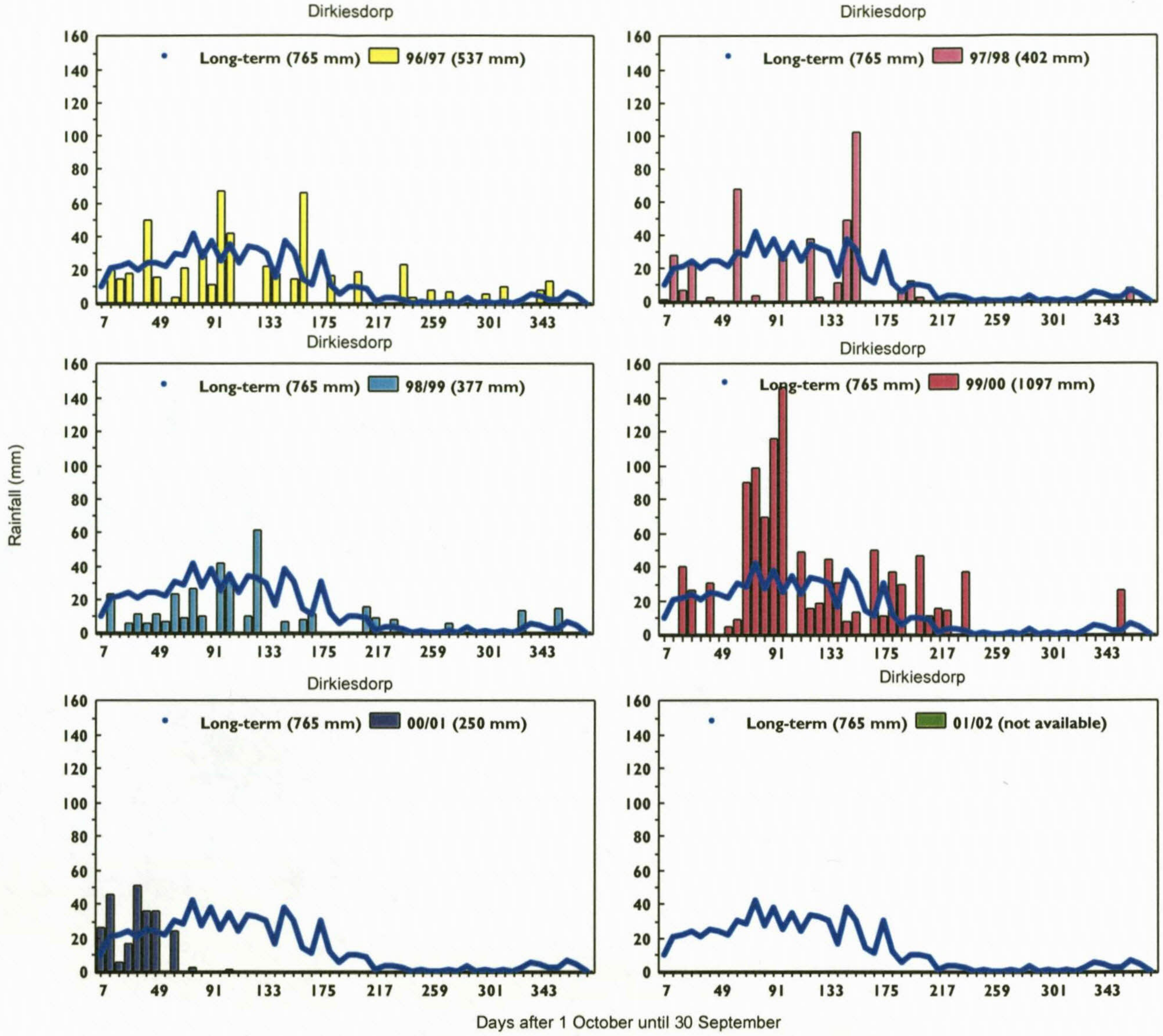
Figures 3.2 continued



Figures 3.2 continued



Figures 3.2 continued



Figures 3.2 continued

Table 3.5 : Seasonal rainfall as a percentage of the long-term rainfall for every growing season at the different localities

Trial	Locality	Season	Rainfall (mm)		Seasonal rainfall as a percentage of the long-term
			Long-term	Seasonal	(%)
1	Lichtenburg	89/90	592	686	116
		90/91	592	676	114
		91/92	592	373	63
		92/93	592	582	98
		93/94	592	684	116
		94/95	592	477	81
		95/96	592	727	123
		96/97	592	925	156
		97/98	592	568	96
2	Wolmaransstad	91/92	494	169	34
		92/93	494	366	74
		93/94	494	403	82
		94/95	494	359	73
		95/96	494	768	155
		96/97	494	665	135
		97/98	494	437	88
3	Koppies (2.24 m)	98/99	620	583	94
		99/00	620	756	122
		00/01[1]	620	274	44
4	Ventersdorp	01/02	589	583	99
5	Viljoenskroon	93/94	578	725	125
		94/95	578	371	64
		95/96	578	987	171
		96/97	578	632	109
		97/98	578	434	75
		98/99	578	698	121
		99/00	578	616	107
		00/01[2]	578	672	116
6	Stilfontein (N x P)	98/99	535	503	94
		99/00	535	653	122
7	Stilfontein (P)	98/99	535	503	94
		99/00	535	653	122
8	Heidelberg (N x P)	91/92	702	431	61
		92/93	702	647	92
		93/94	702	838	119
		94/95	702	436	62
		95/96	702	1049	149
		96/97	702	1001	143
		97/98	702	628	89
9	Heidelberg (Lime x P)	91/92	702	431	61
		92/93	702	647	92
		93/94	702	838	119
		94/95	702	436	62
		95/96	702	1049	149
		96/97	702	1001	143
		97/98	702	628	89
10	Athole	96/97	990	1011	102
		97/98	990	897	91
11	Belfast	96/97	785	627	80
12	Vrede	96/97	654	728	111
13	Koppies (0.90 m)	98/99	620	583	94
		99/00	620	756	122

		00/01[1]	620	274	44
		97/98	654	499	76
14	Dirkiesdorp	96/97	765	537	70
		97/98	765	402	53
		98/99	765	377	49
		99/00	765	1097	143
		00/01[3]	765	250	33

Only rainfall between 1 October and [1] end of December, [2] end of April and [3] end of January was available from the South African Weather Bureau at the time of recording

At Lichtenburg the 1989/90, 1990/91, 1993/94, 1995/96 and 1996/97 seasons received more than the long-term average and therefore the higher rainfall should be reflected in higher yields. However, during 1991/92 and 1994/95 less rain than the long-term average occurred and therefore lower yields were expected, while rainfall during the 1992/93 and 1997/98 seasons corresponded with that of the long-term average. At Wolmaransstad higher rainfall than the long-term average occurred only during the 1995/96 and 1996/97 seasons, while all the other seasons had less rain than the long-term average. The 1991/92 season received the lowest rainfall, i.e. only 34 % of the long-term average and thus yield may have been affected. At Koppies the first season, i.e. 1998/99, received 37 mm of rain less than the long-term average, while the second season, viz. 1999/00, received 136 mm more than the long-term figure. However, not all rainfall data for the 2000/01 season was available and the distribution cannot be reported. During the 2001/02 growing season at Ventersdorp the annual rainfall (583 mm) corresponded 99 % with that of the long-term average (589 mm). At Viljoenskroon more rain occurred during the 1993/94, 1995/96, 1996/97, 1998/99 and 1999/00 seasons than the long-term average, while the 1994/95 and 1997/98 seasons only received 64 and 75 % of the long-term average, respectively. During the latter two seasons below average yields were expected. Although rainfall during the remaining season, i.e. 2000/01, was only recorded between 1 October until the end of April, 16 % more rain than the long-term average occurred. At Stilfontein more rain occurred during the second season (1999/00) than the long-term average, while the amount of rain during the first season (1998/99) corresponded with the long-term average. At Heidelberg, rain that occurred during the 1993/94, 1995/96 and 1996/97 seasons exceed that of the long-term average, while all the other seasons, viz. 1991/92, 1992/93, 1994/95 and 1997/98 had less rain than the long-term average. Rain during the 1991/92 and 1994/95 seasons was significantly less than the long-term average and lower yields were therefore expected. During the 1996/97 season slightly more rain than the long-term average occurred at Athole and Vrede, while only 80 % of the long-term average occurred at Belfast. During the 1997/98 season only 76 % of the long-term average occurred at Vrede and 91 % at Athole. Thus average yields were expected at Athole and Vrede during the 1996/97 season and below average yields at Belfast and Vrede during the 1996/97 and 1997/98 seasons, respectively. At Dirkiesdorp 143 %

of the long-term average occurred during the 1999/00 season corresponding with a higher than average yield expectancy, while much less rainfall was recorded during the 1996/97 until the 1998/99 seasons. During the latter two seasons only approximately 50 % of the long-term average rainfall realized resulting in below average yield expectancies. During the 2000/01 season 33 % of the long-term average rainfall was recorded between October and end of January, but the amount and distribution for the remaining part of the season was uncertain.

3.3 Soil types and properties

Most of the soils at the different localities were not previously classified according to the South African taxonomic soil classification system (Soil Classification Working Group, 1991) and thus soil properties were not recorded. During June and July 2001, all soils were classified, described and analysed according to the above mentioned system as suggested by the Pedology and Data Analysis Staff (1991). Analyses were done on representative samples collected from diagnostic horizons. These condensed detail descriptions and properties of the soils are presented in Appendix 3.1. In addition pictures of all soils are presented in Appendix 3.2. The type, clay content and bulk density of the soils at the different localities is summarized in Table 3.6.

However, it must be mentioned that at the Ventersdorp, Viljoenskroon, Belfast, Athole and Koppies localities profile pits were dug immediately adjacent to the trial areas, while at the other localities profile pits were dug within the boundaries of the trial areas. Thus, in the case of the Heidelberg, Wolmaransstad, Vrede, Stilfontein, Lichtenburg and Dirkiesdorp localities, chemical properties of the soils would probably not have been affected by fertilizer treatments, whereas those of the other localities would probably have been affected to some extent. Soil within the trial area at Lichtenburg varied slightly. Thus, two pits were dug during soil investigation and classification. Both were classified as from the Montagu form with slight differences in coloring of the A-horizons, as well as thickness of the B_1-horizons (see Appendix 3.1), but for the purpose of the study the differences have been ignored. At the Viljoenskroon trial area, soil at the spot that was chosen for the pit to be dug, was classified as a Bloemdal form. The hard plinthic B_3-horizon occurred in a wavy topography, which implied a varying soil depth. However, for the purpose of the study these differences have been ignored.

Table 3.6 : Type, clay content and bulk density of soils at the different localities

Trial	Locality	Soil type[1]		Clay content of soil layers (%)[2]			Bulk density of soil layers (kg m^{-3})		
		Form	Family	0 - 150	150 - 300	300 - 600	0 - 150	150 - 300	300 - 600
							(mm)		
1	Lichtenburg	Montagu	Baden	24.2	26.2	-[3]	1328/1585[6]	1522/1573[6]	-[3]
2	Wolmaransstad	Bloemdal	Roodeplaat	12.4	12.7	17.8	1478[4]	1697[4]	1605[4]
3	Koppies (2.24 m)	Rensburg	Rietkuil	47.0	23.9	19.0	1084[5]	1102[5]	1136[5]
4	Ventersdorp	Hutton	Hayfield	14.3	14.8	16.7	1495/1530[6]	1620/1678[6]	1563/1530[6]
5	Viljoenskroon	Bloemdal	Waldo	8.4	11.7	15.2	1474/1414[6]	1733/1536[6]	1516/1489[6]
6	Stilfontein (N x P)	Bloemdal	Waldo	18.4	24.1	27.5	1688[4]	1547[4]	1459[4]
7	Stilfontein (P)	Bloemdal	Waldo	18.4	24.1	27.5	1688[4]	1547[4]	1459[4]
8	Heidelberg (N x P)	Avalon	Vryheid	17.3	26.3	31.8	1747/1755[6]	1685/1747[6]	1448/1472[6]
9	Heidelberg (Lime x P)	Hutton	Suurbekom	15.7	15.7	22.0	1331/1362[6]	1542/1619[6]	1596/1617[6]
10	Athole	Hutton	Lillieburn	39.4	44.6	39.4	1216/1325[6]	1167/1251[6]	1087/1120[6]
11	Belfast	Avalon	Avondale	13.0	14.4	14.6	1335/1585[6]	1572/1512[6]	1565/1608[6]
12	Vrede	Klapmuts	Napier	17.4	-[7]	-[7]	1477[4]	-[7]	-[7]
13	Koppies (0.90 m)	Rensburg	Rietkuil	47.0	23.9	19.0	1084[5]	1102[5]	1136[5]
14	Dirkiesdorp	Shortlands	Empangeni	44.0	50.1	64.2	1285[8]	1379[8]	1258[8]

[1] - Soil Classification Working Group (1991); [2] - Clay is defined as soil particles < 0.002 mm (Schroeder, 1984; Brady & Weil, 1999); [3] - Saprolite underlying the 150 - 300 mm layer; [4] - As trials were terminated and previous trial areas are being used for other agronomic purposes, bulk densities of the 0 - 150, 150 - 300 and 300 - 600 mm soil volumes were determined, where applicable, and not divided into volumes between and over maize rows; [5] - As Vertic soils are self-mulching, only bulk densities of soil volumes over rows were determined; [6] - Bulk densities of soil volumes over the rows and between rows, respectively; [7] - Because of insufficient soil due to thin and stony horizons, clay content could not be determined; [8] - As fertilizers were broadcast and soil samples were taken from soil volumes between rows, bulk densities of only the volumes between rows were determined.

According to Table 3.6 the trials were conducted on seven soil forms that comprise eleven soil families. The clay content of the top 150 mm soil varied between 8 % at Viljoenskroon to 47 % at Koppies, resulting in several textural classes. Differences in mineralogical, chemical and physical properties between soils are presented in Appendix 3.1.

The determination of bulk density is not a standard procedure when soils are classified, described and analysed as suggested by the Pedology and Data Analysis Staff (1991). Therefore a more detailed description on the determination of bulk density is given. Soil samples for the determination of bulk densities were collected according to a modified core method. According to the core method, as described by Blake (1965), a cylindrical metal sampler is pressed or driven into the soil to the desired depth and is carefully removed to preserve a known volume of sample as it existed *in situ*. The sample is dried to 105 °C and weighed. Bulk density is then determined as the oven-dried mass divided by the field volume of the sample. However, the core method is usually unsatisfactory if more than an occasional stone is present in the soil and if the soil is too wet or dry. The method used in this study involved a self-made sampler with a volume of 500 cm^3 that was driven horizontally into the soil by a hand held hammer. After pits were dug, description and sampling of soil volumes over and between maize rows for the 0 - 150, 150 - 300 and 300 - 600 mm depth intervals, where applicable, were measured and marked onto the wall perpendicular to the maize rows. Three samples were collected within each soil volume and combined (thus 1500 cm^3), where-after bulk density was determined. Although soils varied widely in terms of texture, stoniness and water content, the reported method was the only option available, since bulk densities were required for the conversion of soil P concentration (mg kg^{-1}) to soil P quantity (kg ha^{-1}). The method is illustrated in Appendix 3.3.

For further characterizing, some mineralogical properties of the clay fraction of all soils within the A-horizons, i.e. clay minerals (kaolinite, mica, smectite and inter-stratified minerals), as well as the oxides and hydroxides of Si (quartz), Fe and Al (goethite, hematite and gibbsite), Mn as well as calcite, were determined and summarized in Table 3.7. As indicated in Section 2.3.2.2.1 metal hydrous oxides, aluminium silicates and calcium carbonates are of great importance in sorption processes of P in soil.

The clay fraction of the A-horizons at the different localities differed widely in mineralogical properties (Table 3.7), for example at Lichtenburg, Koppies, Ventersdorp, Stilfontein and Athole it contained 37, 29, 5, 5 and 6 % smectite clay, respectively. This 2:1 type clay mineral is known for swelling and shrinking properties with cation exchange capacities (CEC) ranging between 60 - 100 $cmol_c$ kg^{-1}. Mica is also a 2:1 type clay mineral and can be compared to illite with CEC ranging between 10 - 40 $cmol_c$ kg^{-1} (Brady & Weil, 1999; Olson, Thompson & Wilson, 2000).

However, the swelling and shrinking properties of mica are limited. Soils at Wolmaransstad, Heidelberg, Athole, Belfast and Dirkiesdorp contained no mica in the clay fraction of the A-horizon, those at Lichtenburg, Ventersdorp and Viljoenskroon between 5 and 8 % and those at Koppies, Stilfontein and Vrede between 13 and 15 %. Thus, soil at Koppies contained the highest amount of 2:1 clay minerals. Soil at Dirkiesdorp contains the highest amount of 1:1 clay minerals in the clay fraction of the A-horizon, i.e. 66 % kaolinite followed by Stilfontein with 52 % and Ventersdorp with 42 %. Those at Lichtenburg and Koppies contained 7 %, at Heidelberg (N x P) and Belfast 13 and 14 %, at Wolmaransstad, Heidelberg (Lime x P) and Vrede 21 % and at Athole and Viljoenskroon 27 and 28 %, respectively. The CEC of kaolinite range between 2 - 8 $cmol_c kg^{-1}$ (Brady & Weil, 1999; Olson et al., 2000).

Table 3.7 : Mineralogical properties of the clay fraction within A-horizons of soils at the localities

		Property											
Trial	**Locality**	**Minerals (X-ray diffraction)**						**Oxides (X-ray diffraction)**			**CBD - extraction (free oxides)**		
		Other		**Clay**				**Fe ^{III}**		**Al**	**Fe[2]**	**Al[2]**	**Mn[2]**
		Quartz[1]	**Calcite[1]**	**Kaolinite[1]**	**Mica[1/3]**	**Smectite[1]**	**Interstratified clay minerals[1]**	**Goethite[1]**	**Hematite[1]**	**Gibbsite[1]**			
							(%)						
1	Lichtenburg[4]	37	16	7	5	37	0	0	0	0	0.346	0.050	0.039
2	Wolmaransstad	69	0	21	0	0	10	0	0	0	0.821	0.056	0.026
3	Koppies (2.24 m)	43	0	7	14	29	7	0	0	0	0.264	0.082	0.047
4	Ventersdorp	28	0	42	7	5	0	11	7	0	2.420	0.139	0.087
5	Viljoenskroon	56	0	28	8	0	0	8	0	0	0.626	0.068	0.008
6	Stilfontein (N x P)	25	0	52	13	5	0	0	5	0	2.810	0.110	0.064
7	Stilfontein (P)	25	0	52	13	5	0	0	5	0	2.810	0.110	0.064
8	Heidelberg (N x P)	77	0	13	0	0	0	10	0	0	0.989	0.140	0.018
9	Heidelberg (Lime x P)	73	0	21	0	0	0	0	6	0	1.670	0.073	0.028
10	Athole	39	0	27	0	6	0	17	0	11	4.600	1.571	0.004
11	Belfast	86	0	14	0	0	0	0	0	0	0.532	0.140	0.002
12	Vrede	64	0	21	15	0	0	0	0	0	0.447	0.080	0.024
13	Koppies (0.90 m)	43	0	7	14	29	7	0	0	0	0.264	0.082	0.047
14	Dirkiesdorp	19	0	66	0	0	0	15	0	0	3.350	0.772	0.005

[1] - Mineralogy clay analysis (Velde, 1992); [2] - CBD method using atomic absorption spectrophotometer (The Non-affiliated Soil Analysis Work Committee, 1990); [3] - Because of overlapping properties, sum of mica and illite ; [4] - Average of two soil profiles

Quartz is a crystalline silica (SiO_2) and an important rock-forming mineral. Next to feldspar it is the most common mineral, occurring either in colourless and transparent hexagonal crystals with varying colour or in crystalline or cryptocrystalline masses. It is commonly the dominant constituent in the sand fraction of soils, often with red or yellowish coatings of iron oxides (Van der Watt & Van Rooyen, 1995). All soils contain quartz within the clay fraction of the A-horizons, but at differing concentrations. Soils at Heidelberg and Belfast contained between 73 and 86 %, those at Viljoenskroon, Vrede and Wolmaransstad between 56 and 69 %, those at Lichtenburg, Athole and Koppies between 37 and 43 %, and those at Dirkiesdorp, Stilfontein and Ventersdorp between 19 and 28 %, respectively (Table 3.7).

Iron and aluminium oxide surfaces have a strong affinity for the oxyanions of P and some transition metals and therefore play a significant role in the environmental cycling of these elements. Significant correlations have been found between the sorption of heavy metals, anions such as phosphate, and the content and mineralogy of Fe and Al oxides. Goethite (α-FeOOH) and hematite (α-Fe_2O_3) are the two most common oxyhydroxide and oxide of iron in soils, respectively. Goethite consists of double chains of edge-shared octahedra that are joined to other double chains by sharing corners and by hydrogen bonds. Hematite consists of sheets of edge-shared octahedra with two-thirds of the available octahedral sites filled with Fe^{3+}. They are both produced by the weathering of iron-containing primary silicate minerals. The iron is commonly in the low-valent state, which is released but quickly oxidized to the very insoluble trivalent form. Goethite occurs with a strong yellowish-brown colour and with a typical needle and laths crystal shape and tends to be dominant in the temperate and more moist zones. Hematite with its deep red colour is more prominent and even dominant in tropical or drier conditions. Gibbsite [γ-$Al(OH)_3$] is the most common oxide of aluminium found in soils and is a product of weathering of a variety of primary aluminosilicates. It consists of sheets of edge-shared octahedra with two-thirds of the available octahedral sites filled with Al^{3+}. Hydrogen ions replace the base-forming cations and the mineral framework breaks down, releasing the aluminium and silicon. The aluminium released by the breakdown of some basic rocks, such as gabbro and basalt, commonly precipitates as gibbsite directly. The weathering of acid rocks, such as granite and gneiss, may first produce kaolinite or halloysite that, upon further weathering, yields gibbsite. Thus gibbsite represents the most advanced stage of weathering in soils. For simplicity, above mentioned oxides can be described as Fe and Al oxide clays. They vary in structure and are not as sticky and plastic as the layer silicate clays on which they are commonly found as coatings. The surface charge varies with pH. At high pH values, the particles carry a small negative charge that is balanced by adsorbed cations. In very acid soils some Fe and Al oxides carry a nett positive charge and attract negatively charged anions instead of cations (Brady & Weil, 1999; Kämf, Scheinost & Schulze, 2000). Only soils at Ventersdorp, Viljoenskroon, Heidelberg (N x P), Dirkiesdorp and Athole contained goethite in the clay fraction of the A-horizons, ranging between 8 and 17 %, while only that of Athole contained 11 % of gibbsite (Table 3.7). Only soils at Ventersdorp, Stilfontein and Heidelberg (Lime x P) contained between 5 and 7 % hematite within the clay fraction of the A-horizons (Table 3.7).

Calcite, mostly as $CaCO_3$, is one of the two important minerals occurring in varying proportions in limestones. The other is dolomite, as $CaMg(CO_3)_2$ (Brady & Weil, 1999). Calcite is usually white, colourless, or in pale shades of grey, yellow and blue and is readily effervescent in cold dilute hydrochloric acid (Van der Watt & Van Rooyen, 1995). Lichtenburg is the only locality with a significant calcite content in the clay fraction of the A-horizon, i.e. 16 % (Table 3.7).

3.4 Experimental layouts and treatments

The fertilizer treatments and experimental layouts for all trials are summarized in Table 3.8.

Table 3.8 : Fertilizer treatments and experimental layouts for all trials

Trial	Locality	Application rates (kg ha^{-1}) or number of P sources		Statistical	Number of :	
		P	N[1], K[2], Lime[3], P sources[4]	layout	Plots	Replicates
1	Lichtenburg	0, 6, 11, 17[6]	0, 36, 72, 108[1]	Randomized block	64	4
2	Wolmaransstad	0, 5, 10, 20, 40, 60	0, 20, 40, 80, 120[1]	Factorial lattice	108	3
3	Koppies (2.24 m)	0, 35, 70, 105, 140	0, 40, 80, 120, 160[1]	Randomized block	56	2
4	Ventersdorp	0, 15, 30, 45, 60	0, 40, 80, 120, 160[1]	Randomized block	56	2
5	Viljoenskroon	0, 10, 20, 40, 60	0, 40, 80, 120, 180[1]	Randomized block	75	3
6	Stilfontein (N x P)	0, 10, 20, 30, 40, 50	0, 34, 70, 105, 140, 175[1]	Randomized block	72	2
7	Stilfontein (P)	0, 15, 30, 45, 60, 75, 90	9[4]	Randomized block	126	2
8	Heidelberg (N x P)	0, 5, 10, 20, 40, 60	0, 40, 80, 120, 180[1]	Randomized block	108	3
9	Heidelberg (Lime x P)	0, 10, 20, 40	0, 750, 1500, 2250, 3000[3]	Randomized block	80	4
10	Athole	0, 15, 30, 45, 60	3[4]	Randomized block	42	3
11	Belfast	0, 15, 30, 45, 60	3[4]	Randomized block	45	3
12	Vrede	0, 15, 30, 45, 60	3[4]	Randomized block	48	3
13	Koppies (0.90 m)	0, 35, 70, 105, 140	0, 40, 80, 120, 160[1]	Randomized block	56	2
14	Dirkiesdorp	0, 30, 60, 120	0, 60, 120, 180[1] / 0, 50, 100, 150[2]	Randomized block	64[5]	1

[1] - N application rates; [2] - K application rates; [3] - Lime application rates; [4] - Number of P sources; [5] - The Dirkiesdorp plots were split three ways for three rotation systems, i.e. maize in monoculture, maize after soybean and soybean after maize. For the purpose of this study only maize in monoculture will be reported; [6] - During the last growing season at Lichtenburg the P application rates were doubled, i.e. 0, 12, 22 and 34 kg P ha^{-1}, therefore this season was statistically analysed separately from the previous seasons.

At the majority of localities N x P fertilizer trials with different application rates were conducted, i.e. Lichtenburg, Wolmaransstad, Koppies, Ventersdorp, Viljoenskroon, Stilfontein and Heidelberg, while a N x P x K trial was conducted at Dirkiesdorp. In all instances N, P and K fertilizers used for amendments were limestone ammonium nitrate (LAN = 28 % N), double super phosphate (Maxifos = 20 % P) and potassium chloride (KCl = 50 % K), except where otherwise specified. At Heidelberg, a second trial was conducted on a different soil (Table 3.6) using lime x P treatments. At Stilfontein, Athole, Belfast and Vrede, P source trials were conducted to compare the efficiency of different sources at different application rates. Three P sources were compared at Athole, Belfast and Vrede, but as these trials were part of a contract research agreement, only the reactions on Maxifos have been included in this study. All the trials, other than the N x P and N x P x K ones, were conducted at sufficient levels of N and K. At Stilfontein nine different P sources were compared with each other (Table 3.9). Because of differences in composition in terms of N, P, K and S content, it was necessary to add additional N, K and S to most of the treatments, in order to balance the rates of application of these elements. Therefore, all treatments that contained less than 100 kg N ha^{-1}, were supplemented with LAN to a total of 100 kg N ha^{-1}. All treatments thus received a N application of 100 kg N ha^{-1} at planting, except the Agrigro source treatment (Agrigro, s.a.) which, because of its N composition, already received 120, 150 and 180 kg N ha^{-1} at the three highest P application rates. In addition all treatments received a K application of 20 kg K ha^{-1}, as KCl at planting. Except for the super phosphate and Agrigro source treatments, all other treatments received an additional S application of 20 kg ha^{-1} as Tiger(90) from Sunbelt Chemicals Inc. (s.a.). The S applications through the super phosphate source were 13, 26, 39, 51, 64 and 77 kg ha^{-1} and through the Agrigro source 47, 74, 100, 177, 154 and 181 kg ha^{-1} for the respective P application rates. All treatments also received a side-dressing of 20 kg N ha^{-1} as LAN, that was knifed-in 4 to 6 weeks after planting. This implicates a total N application of 120 kg N ha^{-1}, except for the Agrigro source treatment which received a total of 140, 170 and 200 kg N ha^{-1} at the three highest application rates. However, for the purpose of the study only reactions on Maxifos were considered.

Table 3.9 : Phosphorus sources that were compared at the Stilfontein trial, as well as their N, P, K and S composition as provided by the manufacturers

	Source	Type	Manufacturer / Distributor	Composition (%)			
				N	: P	: K	: S
S1	DAP	Granules	Sasol	18.0	22.0	0.0	0.0
S2	MAP	Granules	Sasol	11.0	22.0	0.0	0.0
S3	Agrifos	Granules	Megakor	0.0	10.2	1.1	0.0
S4	Grofos	Granules	Greenlands	0.0	10.0	1.0	0.0
S5	Super phosphate	Granules	Kynoch	0.0	10.5	0.0	9.0
S6	Maxifos	Granules	Kynoch	0.0	20.0	0.0	2.0
S7	Kynosol (phosphoric acid)	Liquid	Kynoch	0.0	23.0	0.0	1.0
S8	Organoflo-fos	Liquid	Organoflo/Agrigro	5.5	8.2	0.0	0.0
S9	Agrigro	Granules	Organoflo/Agrigro	14.0	7.0	1.0	12.5

At all localities, except Dirkiesdorp, P treatments and 20 kg N ha^{-1} together with other fertilizer amendments were band placed at planting 50 mm away and 50 mm below the seed, where-after the remaining N was knifed-in as a side-dressing four to six weeks after planting. At Dirkiesdorp however, all P and K, as well as half of the N were broadcast immediately before planting, where-after it was soil incorporated by a single discing. The remaining N was broadcast and incorporated four to six weeks after planting.

Both the gross and nett plot sizes, dimensions and rows at the various trials are given in Table 3.10. The maize cultivars, row widths and plant densities for each trial are shown in Table 3.11. Unfortunately, not all planting dates at the different localities were recorded. However, the general practice is to plant maize from the beginning until middle October in the eastern maize producing areas (Heidelberg, Athole, Belfast, Vrede and Dirkiesdorp) and from the middle of November until the middle of December in the western maize producing areas (Lichtenburg, Wolmaransstad, Koppies and Ventersdorp).

Table 3.10 : Gross and nett plot sizes, dimensions and number of rows for all trials

		Gross plot			**Nett plot**		
Trial	**Locality**	**Size (m^2)**	**Dimensions (m)**	**Number of rows**	**Size (m^2)**	**Dimensions (m)**	**Number of rows**
1	Lichtenburg	108.0	12.0 x 9.0	4	45.0	10.0 x 4.5	2
2	Wolmaransstad	108.0	12.0 x 9.0	4	45.0	10.0 x 4.5	2
3	Koppies (2.24 m)	108.0	12.0 x 9.0	4	36.0	8.0 x 4.5	2
4	Ventersdorp	108.0	12.0 x 9.0	4	36.0	8.0 x 4.5	2
5	Viljoenskroon	75.0	10.0 x 7.5	5	36.0	8.0 x 4.5	3
6	Stilfontein (N x P)	60.0	10.0 x 6.0	4	24.0	8.0 x 3.0	2
7	Stilfontein (P)	60.0	10.0 x 6.0	4	24.0	8.0 x 3.0	2
8	Heidelberg (N x P)	60.0	10.0 x 6.0	4	24.0	8.0 x 3.0	2
9	Heidelberg (Lime x P)	60.0	10.0 x 6.0	4	24.0	8.0 x 3.0	2
10	Athole	54.0	15.0 x 3.6	6	23.4	13.0 x 1.8	4
11	Belfast	43.2	12.0 x 3.6	6	18.0	10.0 x 1.8	4
12	Vrede	43.2	12.0 x 3.6	6	18.0	10.0 x 1.8	4
13	Koppies (0.90 m)	54.0	10.0 x 5.4	6	14.4	8.0 x 1.8	2
14	Dirkiesdorp	72.0	12.0 x 6.0	8	15.0	10.0 x 1.5	2

Table 3.11 : Maize cultivars, row widths and plant densities for all trials

Trial	Locality	Cultivar	Row width (m)	Plant density (plants ha^{-1})
1	Lichtenburg	PAN 473	2.24	16000
2	Wolmaransstad	PAN 6249/6578 [1]	2.24	18000
3	Koppies (2.24 m)	PAN 6479	2.24	19000
4	Ventersdorp	PAN 6479	2.24	24000
5	Viljoenskroon	PAN 6549	1.50	22000
6	Stilfontein (N x P)	PAN 6479/SNK [2]	1.50	22700
7	Stilfontein (P)	PAN 6479/SNK [2]	1.50	22700
8	Heidelberg (N x P)	PAN 6549	1.50	17700
9	Heidelberg (Lime x P)	PAN 6549	1.50	26000
10	Athole	PNR 6140	0.90	22030
11	Belfast	PNR 6140	0.90	34493
12	Vrede	SNK 2021	0.90	44062
13	Koppies (0.90 m)	PAN 6479	0.90	24000
14	Dirkiesdorp	PAN 6242/6568 [3]	0.75	40000

[1] - During the first growing season the maize cultivar PAN 6429 was planted, where-after PAN 6578 was planted during the remaining trial period; [2] During the first growing season the maize cultivar PAN 6479 was planted, where-after it was replaced by an unknown SNK cultivar, provided by the farmer, [3] - For the first two seasons PAN 6242 was planted, where-after PAN 6568 was planted.

3.5 General agronomic practices

The general agronomic practices are summarized in Table 3.12. The agronomic practices differed somewhat between trials due to variation in circumstances. As expected, very similar agronomic practices were applied for the two trials at Koppies and for the two trials at Stilfontein. However, at Athole, Belfast and Vrede the agronomic practices were also very similar.

Table 3.12 : General agronomic practices followed for all trials

Trial	Locality	Agronomic practices
1	Lichtenburg	Before the establishment of the trial the area was under natural grassland. During 1989 the area was ploughed and a seedbed was prepared. Since no other deficiencies were found, no extra fertilization other than the treatments was applied. An alternative controlled traffic system with chisel ploughing to a depth of 300 mm was practised. All weed control was carried out mechanically. During the last three seasons, i.e. 1994/95, 1995/96 and 1996/97, seed was treated with Gaucho for insects. Planting practices used in this trial differed from the others in that maize rows were planted on the same rows every second season, therefore soil volumes over maize rows and volumes between maize rows exchanged position every season with the same positions every second season. Plant material after each season was first left to decay and then cut in by discing.
2	Wolmaransstad	Soil samples to determine the nutrient status of the soil were collected before commencement of the trial and since no other deficiencies were found, no extra fertilization other than the treatments was applied. After harvesting each season, the soil was tilled to a depth of 100 mm, for optimal water infiltration as well as weed control. Before planting each season the same cultivation procedure was repeated. Weed control was carried out chemically during planting, i.e. a mixture of Lasso and Atrazine according to label instructions. During the season weed was controlled mechanically, or by hand. Seed was treated each season with Promed for pests and insects.
3	Koppies (2.24 m)	Soil samples to determine the nutrient status of the soil were collected before the trial commenced and because no deficiencies were found, no extra fertilization, other than the treatments was applied. After harvesting no cultivation was done. Before planting the soil was tilled and disced or rotavated to a depth of 100 mm for seedbed preparation. Weed control was accomplished by spraying Dual plus Gardomil pre-emergence and afterwards during the season by hand. Seed was treated with Gaucho and Decis was mixed with the pre-emergence herbicides for the control of insects. After emergence at varying growth stages, Bulldog pellets were applied for the control of stalk borer.
4	Ventersdorp	Soil samples to determine the nutrient status of the soil were collected approximately six months prior to commencement of the trial. The trial area was deep ripped and lime was applied one month prior to planting at a rate of 15 t ha^{-1} and ploughed in as deep as possible. Seedbed preparation was carried out by discing and tine harrowing, where-after planting proceeded. Weed control was carried out chemically during planting, i.e. a mixture of Gardomil Super and Dual according to label instructions. Seed was treated with Gaucho and Decis was mixed with the pre-emergence herbicides for the control of insects. After emergence at varying growth stages, Bulldog pellets were applied for the control of stalk borer. During the growing season Yellow Nutsedge was controlled chemically by spraying of Servian.
5	Viljoenskroon	Soil samples to determine the nutrient status of the soil were collected prior to the commencement of the trial. Since this soil was low in K and Mg content, 40 kg K ha^{-1} as potassium chloride and 36 kg Mg ha^{-1} as magnesium oxide were used to supplement soil volumes over the rows. No applications were made to soil volumes between rows. Controlled traffic practice with rip on the row cultivation to a depth of 500 mm after harvesting was applied. Seedbed preparation and mechanical weed control were executed by tine harrows. Weed control was carried out chemically during planting, i.e. a mixture of Gardomil Super and Dual according to label instructions. Decis was also mixed with the herbicides for the control of the maize stalk borer. During the season weed was controlled mechanically or by hand. Seed was treated with Gaucho for insect control. After emergence at varying growing stages, Bulldog pellets were applied for the control of stalk borer.
6	Stilfontein (N x P)	The field was ploughed to a depth of 300 mm during November 1998, approximately three weeks prior to planting. Soil samples to determine the nutrient status of the soil were collected before the trial commenced. No other deficiencies were found, therefore no extra fertilization, other than the treatments was applied. After harvesting the first season, the soil was ploughed to incorporate remaining plant residues and weed control. Seedbed preparation was carried out immediately before planting with a chisel plough. During planting, a mixture of Gardomil, Dual and Gramoxzone were applied according to the label instructions, for the control of weeds. Seeds were treated with Gauco for insects. Decis and Currater were also applied for the same purpose. During the season weeds were controlled by hand. After emergence at varying growing stages, Bulldog pellets were applied for the control of stalk borer.

7	Stilfontein (P)	The P source trial that was established on a plot adjacent to the N x P trial was subjected to the same treatment and inputs as for the N x P trial above.
8	Heidelberg (N x P)	Soil samples to determine the nutrient status of the soil were collected prior to commencement of the trial. An amount of 1 t ha^{-1} micro fine calcitic lime was broadcasted and incorporated approximately six weeks before commencement. Controlled traffic practices with rip on the row cultivation to a depth of 400 mm after harvesting was applied. Seedbed preparation and mechanical weed control were executed by tine harrows. Weed control was carried out chemically during planting, i.e. a mixture of Gardomil Super and Dual according to label instructions. Decis was also mixed with the herbicides for the control of the maize stalk borer. During the season weed was control mechanically or by hand. Seed was treated with Gaucho for insect control.
9	Heidelberg (Lime x P)	Soil samples to determine the nutrient status of the soil were collected prior to commencement of the trial. Since the soil was low in K content, 16 kg K ha^{-1} as potassium chloride was banded with planting each season together with N and P treatments. No amendments were made to soil volumes between rows. The same procedures were followed as at the N x P trial above.
10	Athole	Soil samples to determine the nutrient status of the soil were collected prior to commencement of the trial. Since no deficiencies were found and no extra fertilizers, other than the treatments were applied. Cultivation practices followed at locality are unknown, but it is assumed that mouldboard and chisel ploughing were the primary cultivation practices. Decis and Currater were applied for insect control, as well as Gaucho as a seed treatment for the same purpose. During the season weeds were controlled by hand.
11	Belfast	The same general agronomical practices were followed as at the Athole trial
12	Vrede	The same general agronomical practices were followed as at the Athole trial
13	Koppies (0.90 m)	Soil samples to determine the nutrient status of the soil were collected before the trial commenced and because no deficiencies were found, no extra fertilization, other than the treatments was applied. After harvesting no cultivation was done. Before planting the soil was tilled and disced or rotavated to a depth of 100 mm for seedbed preparation. Weed control was accomplished by spraying Dual plus Gardomil pre-emergence and afterwards during the season by hand. Seed was treated with Gaucho and Decis was mixed with the pre-emergence herbicides for the control of insects. After emergence at varying growth stages, Bulldog pellets were applied for the control of stalk borer.
14	Dirkiesdorp	Soil samples were collected before the trial commenced to determine the nutrient status of the soil. Dolomitic limestone (3 t ha^{-1}) and mineral gypsum (9 t ha^{-1}) were applied uniformly across the trial site and immediately incorporated by double discing and ploughing. No other amendments were made. After harvesting each season most of the plant material was removed where-after a primary discing operation was carried out. Discing was also the primary cultivation method during the winter months for weed control, as well as for seedbed preparation. Weed control was accomplished by spraying Dual plus Gardomil pre-emergence. Cypermethrin, Gaucho and Punch-Extra were used for the control of insects.

3.6 Collection and processing of data

3.6.1 Soil phosphorus contents

Soil sampling was partially or completely carried out according to the method presented in Figure 3.3, except for the Dirkiesdorp locality where treatments were broadcast. More detail on soil sampling at each trial is given in Table 3.13. According to this method samples for the soil volume over a row should be taken alongside each other with a soil auger having a diameter of at least 76 mm, at three positions and spread evenly over a 300 mm wide strip, implicating three samples per row. After the samples are collected, they should then be mixed to represent the soil volume over rows. Care should be taken that the sampled areas should overlap each other, thus ensuring that all fertilizer enriched zones are included. According to Landman (1995) the enriched zones over maize rows due to band placement of fertilizer at distances of not more than 50 mm away from and 50 mm below the seed, as well as side-dressings of not more than 100 mm away from the maize row will result in an approximate 300 mm wide strip over the rows (F.G. Adriaanse, 2001, ARC-Grain Crops Institute, Potchefstroom, South Africa: Personal communication). Samples of the soil volumes between rows should be taken with the same auger at both sides of a row, at distances of 25 and 50 % of the row width respectively, implicating four samples which should be mixed to represent the soil volumes between rows at each sampling point. Five sampling points were proposed on a field basis. Two to three sampling points were however used on experimental plots for the purpose of this study. Since band placed P is usually placed at a depth of 100 mm, most residual inorganic P occurs in the top 150 mm soil. For this reason all calibrations in this study were restricted to a depth of 0 to 150 mm.

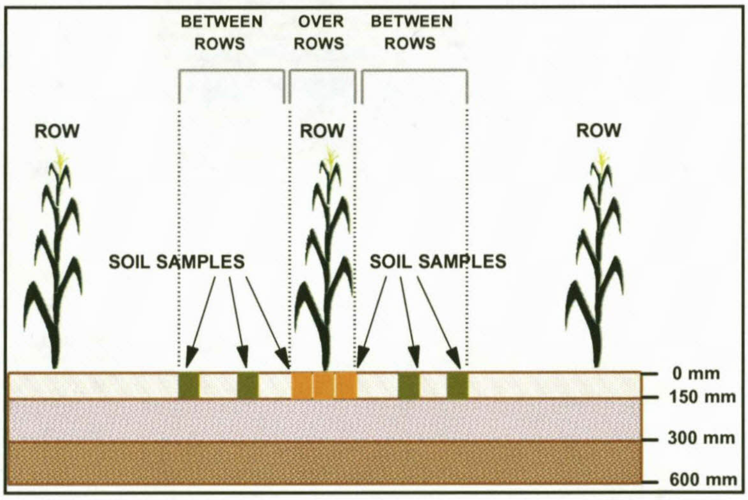


Figure 3.3 : Soil sampling method (LNR-Instituut vir Graangewasse, 1994; Landman, 1995).

For all trials, except those at Lichtenburg and Heidelberg (Lime x P), soil sampling was carried out four to six weeks after planting, viz. approximately two weeks after side-dressing of N. For the Lichtenburg trial it was carried out after harvesting and for the Heidelberg (Lime x P) trial before side-dressing. However, detailed information on soil sampling at the different trials is summarized in Table 3.13.

After sampling soil samples were transferred to the laboratory within 24 hours where they were dried at room temperature, ground if required, sieved through a 2 mm sieve and stored until analysis. All samples were analysed for extractable P according to the Ambic 1 method while only some of the samples from each locality were analysed for extractable P according to the Bray 1 method (The Non-affiliated Soil Analysis Work Committee, 1990).

Table 3.13 : Soil sampling details on timing, seasons and soil volumes

Trial	Locality	Soil samples used for the determination of soil and plant reactions as collected from the 0 - 150 mm soil layer :
1	Lichtenburg	- for all nine growing seasons, i.e. from 1989/90 until 1997/98, after harvesting from soil volumes over and between rows. Thus soil and plant comparisons were made with extractable P measurements at the end of a growing season.
2	Wolmaransstad	- for all seven growing seasons, i.e. from 1991/92 until 1997/98, from soil volumes over the rows after side-dressing. Extractable P concentrations of samples during the first season were low and very much the same and therefore excluded from analysis. The possibility exists that samples were collected from the soil volumes between rows during this year. Samples from the soil volumes between rows during 1992/93 until 1994/95 were collected after harvesting. Those of the remaining seasons were collected after side-dressing together with those of the volumes over the rows.
3	Koppies (2.24 m)	- after side-dressing from the 1998/99 until the 2000/01 season in soil volumes over and between rows.
4	Ventersdorp	- after side-dressing from the 2001/02 season in soil volumes over and between rows.
5	Viljoenskroon	- after side-dressing in the soil volumes over the rows for all seasons, i.e. 1993/94 until 2000/01. Samples from volumes between rows were only collected from the 1994/95 until the 2000/01 season. During this period samples were collected before planting from 1994/95 until the 1997/98 season, but after side-dressing from 1998/99 to the 2000/01 seasons. However, during the 2000/01 season samples were only collected from P treatments at the highest N rate, i.e. 180 kg N ha^{-1}.
6	Silfontein (N x P)	- for both growing seasons, i.e. 1998/99 and 1999/00, after side-dressing in the soil volumes over and between rows.
7	Stilfontein (P)	- for both growing seasons, i.e. 1998/99 and 1999/00, after side-dressing in the soil volumes over the rows.
8	Heidelberg (N x P)	- for five growing seasons, i.e. from 1993/94 until 1997/98, after side-dressing in soil volumes over the rows and before planting in soil volumes between rows. Samples collected for the 1991/92 and 1992/93 seasons are incomplete and will therefore not be included in this study.
9	Heidelberg (Lime x P)	- for all seven growing seasons, i.e. from 1991/92 until 1997/98 in the soil volumes over the rows. For the first four seasons (1991/92 until 1994/95) samples were collected after planting, but before side-dressing. However, for the remaining growing seasons samples were collected after side-dressing.
10	Athole	- for the 1996/97 season soil samples were collected after planting, before side-dressing in soil volumes over the rows. During the 1997/98 season samples were collected in the same manner, but after side-dressing.
11	Belfast	- after planting, but before side-dressing, for the 1996/97 growing season, but only in soil volumes over the rows.
12	Vrede	- after planting, but before side-dressing, for the 1996/97 and 1997/98 growing seasons, only in soil volumes over the rows.
13	Koppies (0.90 m)	- after side-dressing for the 1998/99 until the 2000/01 season in soil volumes over and between rows.
14	Dirkiesdorp	- after side-dressing from the 1998/99 until the 2000/01 season from the soil volumes between rows. Because fertilizer were broadcast, it was assumed that samples from volumes between rows will be representative of the total soil volume. The narrow row spacing of 750 mm and the high plant density made soil sampling within rows very difficult if required.

3.6.2. Grain yield determinations

Grain was harvested at all trials after maturity and yields were corrected to 12.5 % moisture content for each plot. General information regarding grain yield data that was recorded at the different trials is summarized in Table 3.14. At most localities the number of plants per nett plot were recorded together with grain yield during harvesting. The purpose of this was to determine whether or not the number of plants per plot contributed to differences in grain yield between plots and in such circumstances the number of plants per plot was used as a covariant in analyses of variance for grain yield.

Table 3.14 : General information on the accumulation of grain yield data for all trials

Trial	Locality	Information
1	Lichtenburg	Yield was recorded from the 1989/90 until the 1997/98 season. Because P application rates were doubled during the last season, this season was analysed separately from the others. Number of plants per nett plot was not recorded.
2	Wolmaransstad	Yield was recorded for all seven seasons, i.e. 1991/92 until 1997/98. Number of plants per nett plot was only recorded during three seasons, i.e. 1992/93, 1993/94 and 1997/98, thus implicating that it cannot be used in statistical analysis over seasons.
3	Koppies (2.24 m)	Yield and number of plants per nett plot were recorded for all three seasons, i.e. 1998/99 until 2000/01.
4	Ventersdorp	Yield and number of plants per nett plot were recorded for the 2001/02 season.
5	Viljoenskroon	Yield and number of plants per nett plot were recorded for all eight seasons, i.e. 1993/94 until 2000/01.
6	Stilfontein (N x P)	Yield and number of plants per nett plot were recorded for both seasons, i.e. 1998/99 and 1999/00.
7	Stilfontein (P)	Yield and number of plants per nett plot were recorded for both seasons, i.e. 1998/99 and 1999/00.
8	Heidelberg (N x P)	Yield and number of plants per nett plot were recorded for all seven seasons, i.e. 1991/92 until 1997/98.
9	Heidelberg (Lime x P)	Yield and number of plants per nett plot were recorded for all seven seasons, i.e. 1991/92 until 1997/98.
10	Athole	Due to cattle and porcupine damage no yield was harvested for the 1996/97 or 1997/98 seasons.
11	Belfast	Yield for the 1996/97 season was recorded, but the number of plants per nett plot was not recorded.
12	Vrede	Yield and number of plants per nett plot were recorded for both seasons, i.e. 1996/97 and 1997/98 seasons.
13	Koppies (0.90 m)	Yield and number of plants per nett plot were only recorded for the first and third seasons, i.e. 1998/99 and 2000/01. During the second season yield was destroyed by porcupines and a veld fire.
14	Dirkiesdorp	Yield and number of plants per nett plot were recorded for the 1998/99, 1999/00 and 2000/01 seasons. As already reported, data from the 1996/97 and 1997/98 seasons were not available.

3.7 Processing of data

Statistical analyses as explained in Chapters 4, 5 and 6 were carried out using the Statgraphics (Manugistics, 1998) and Genstat (Genstat, 2000) software and relationships were determined using Costat (CoHort, 1995).

CHAPTER 4

RELATIONSHIPS BETWEEN AMBIC 1 AND BRAY 1 EXTRACTABLE PHOSPHORUS

4.1 Introduction

Knowledge on the ability of soils to supply P to plants is essential for sustainable crop production. Therefore numerous methods have been developed for the estimation of plant available P. Most of these methods involve a chemical extraction procedure. Unfortunately, there is no chemical extraction procedure which is well correlated with plant uptake under all conditions (Prasad & Power, 1997).

However, chemical extraction procedures commonly used for P are based on chemical principles that relate mainly to P minerals found in soils. These minerals can dissolve, or adsorbed P can be released, to resupply soil solution P when this P is taken up by plants. Chemical extractants for P simulate this process, because they reduce the Al, Fe and Ca in the soil solution through either complexation or precipitation. As the Al, Fe and Ca in the soil solution decreases during extraction, the Al-P, Fe-P and Ca-P minerals dissolve to resupply Al, Fe and Ca to the soil solution. The P in the soil solution concurrently increases, which provides a measure of the soil's ability to supply P to plants (Havlin et al., 1999).

Therefore, depending on the extraction solution used, various forms and amounts of P in soil can be estimated (Sharpley, 2000). As far as the Bray 1 extractant (0.025 mol dm^{-3} HCl + 0.03 mol dm^{-3} NH_4F; Bray & Kurtz, 1945) is concerned the main forces behind the solubilization of Al-, Fe- and Ca-phosphates are the protonation of PO_4^{3-}, complexation of fluoride with Al^{3+} and Fe^{3+} and precipitation of CaF_2. In the case of the Ambic 1 extractant (0.25 mol dm^{-3} NH_4HCO_3 + 0.01 mol dm^{-3} $(NH_4)_2$ EDTA + 0.01 mol dm^{-3} NH_4F; Van der Merwe, Johnson, Ras & Schultz, 1981; The Non-affiliated Soil Analysis Work Committee, 1990) the effect of protonation of PO_4^{3-} is less due to the relatively high pH of 8.3 caused by the presence of NH_4HCO_3. In this instance the complexation of Al^{3+}, Fe^{3+} and Ca^{2+} by EDTA is the main solubilizing factor, with the effect of the fluoride being minor (Thomas & Peaslee, 1973; Olsen & Sommers, 1982; Hahne, Van der Merwe & Loock, 1988). Thus different forms and amounts of soil P will be extracted by these Bray and Ambic procedures. The Ambic extraction method was developed by Van der Merwe, Johnson & Ras (1984) by modifying the ISFEI extraction method of Hunter (1974). Instead of $NaHCO_3$ and Na-EDTA, NH_4HCO_3 and NH_4-EDTA are respectively used for the preparation of the extractant, and the pH of the extractant is adjusted using NH_4OH and not NaOH. Considering the chemicals, similar forms and amounts of soil P should therefore be extracted by these two methods.

However, little work on the relationships of either ISFEI or Ambic 1 with Bray 1 has been published, despite the fact that much work has been done internationally and locally comparing various P extraction methods. For example internationally Mallarino & Blackmer (1992) compared the efficacy of three extractants for determining critical extractable P concentrations for maize, i.e. Bray 1, Mehlich 3 and Olsen. Locally Möhr (1975b), Van der Merwe (1978), Dijkhuis (1979), Venter (1979) and Venter & Forbes (1983) compared the two extractants ISFEI and Bray 1 with Bray 2 for various soil combinations, i.e. alkaline, acid and very acid soils, as well as mixed soils. Much work has also been done by Thompson (s.a.) in the Western Cape on relationships between the four extractants Bray 1, Bray 2, ISFEI and Mehlich 3 with citric acid. Only Buys & Venter (1980) and Venter & Forbes (1983) reported on the relationships between either ISFEI and Bray 1 or Ambic 1 and Bray 1 extractable P values.

The evaluation of soil P status and the calibration of soil test values with yield response data form an essential part of the prediction of optimum rates of P fertilization. However, the South African fertilizer industry prefers to use Bray 1 extractions for fertilizer recommendations and the ARC-Grain Crops Institute, Ambic 1 extractions for calibration research. Therefore the objective of the study was to establish relationships between the P extracted by the two methods firstly over soils and secondly in specific soils and thirdly, if possible, to relate differences in these relationships between specific soils to soil properties. To date such relationships were determined without taking soil properties into account.

4.2 Procedure

Some general information on the sampling and analyses for soil phosphorus contents is presented in Section 3.6.1. As mentioned all the samples collected from the trials were analyzed for extractable P according to the Ambic 1 method, while only some of the samples were analyzed for extractable P according to the Bray 1 method. However, approximately 3000 samples were analyzed using both methods with the result that there was sufficient data to determine relationships between Ambic 1 and Bray 1 extractable P for each locality. Some relevant information regarding the soil sampling procedures that were used for the determination of these relationships is summarized in Table 4.1

Firstly, simple linear regression analyses were done between the pooled Ambic 1 and Bray 1 extractable

P values from all trials as shown in Table 4.1. This was followed by simple linear regression analyses between the Ambic 1 and Bray 1 extractable P values from each trial, where-after the slopes of these relationships were compared as described by Draper & Smith (1981). Lastly, multiple and simple regression analyses were done to relate these slopes to soil properties of the A-horizons as described in Section 3.3.

Table 4.1 : Soil sampling details on seasons, timing and soil volumes for the determination of relationships between Ambic 1 and Bray 1 extractable P in the top 150 mm soil

Trial	Locality	Details
1	Lichtenburg	1994/95 after harvesting over the rows and during the 1997/98 season after harvesting over and between rows.
2	Wolmaransstad	1994/95 growing season after side-dressing over the rows. During the extent of this trial all extractable P was determined only according to Ambic 1. During 2001 a set of these soil samples was analysed according to both the Ambic 1 and Bray 1 methods and used to establish the relationship.
3	Koppies (2.24 m)	1998/99 and 1999/00 after side-dressing over and between rows.
4	Ventersdorp	2001/02 after side-dressing over and between rows. Data used in comparisons differed from the other localities. As the profile pit was dug outside the trial area in known conditions of high acidity (Appendix 3.1), soil samples analyzed with both the Ambic 1 and Bray 1 extractants for the establishment of relationships between the two extractants, were also analyzed for exchangeable Ca, Mg and Na. The obtained values are recorded and indicated in Appendix 3.1. The average value of each of the mentioned elements was determined over all treatments and used in comparisons.
5	Viljoenskroon	1994/95 and 1997/98 after side-dressing over the rows and 1999/00 before planting over and between rows.
6	Stilfontein (N x P)	1998/99 after side-dressing over and between rows and 1999/00 over and between rows.
7	Stilfontein (P)	1998/99 after side-dressing over and between rows and 1999/00 over and between rows.
8	Heidelberg (N x P)	1994/95 and 1997/98 after side-dressing over the rows.
9	Heidelberg (Lime x P)	1994/95 after side-dressing over the rows and 1997/98 after side-dressing over and between rows.
10	Athole	1996/97 and 1997/98 after side-dressing and before planting over the rows.
11	Belfast	1996/97 after planting before side-dressing over the rows.
12	Vrede	1996/97 and 1997/98 after planting and after side-dressing over the rows.
13	Koppies (0.90 m)	1998/99 and 1999/00 after side-dressing over and between rows.
14	Dirkiesdorp	1998/99 after side-dressing between maize rows.

4.3 Results and discussion

4.3.1 Relationships over soils

In this study where the clay content of the soils ranged from 8.4 to 49.0 % significant linear relationships with R^2-values of 91 % ($P < 0.001$) were obtained between Ambic 1 (Y) and Bray 1 (X) extractable P values and *vice versa* (Table 4.2).

Table 4.2 : Relationships between either Ambic 1 or ISFEI and Bray 1 extractable P values over soils from this and other studies

Study	Number of soils	Clay content (%)	Equation	R^2-value
This study[1]	12	8 - 47	[2]Ambic 1-P = -1.22036 + 0.73596.Bray 1-P	91
Venter & Forbes (1983)	11	8 - 18	[2]Ambic 1-P = 0.252 + 0.804.Bray 1-P	Unknown
Buys & Venter (1980)	Unknown	Unknown	[3]ISFEI 1-P = 1.07 + 1.49. Bray 1- P	90

[1] Bray 1-P (mg kg^{-1}) = 3.82137 + 1.23085Ambic 1-P (mg kg^{-1}); [2] Gravimetric; [3] Volumetric

Venter & Forbes (1983) reported an equation for the linear relationship between Ambic 1 and Bray 1 extractable P values for soils that ranged between 8 and 18 % in clay content. No R^2-value to indicate the reliability of this equation was reported by them, since the slope and intercept of this equation are mathematical means, calculated from the slopes and intercepts of the equations established for each of 11 soils (five Avalons, one Clovelly, four Huttons and one Pindene classified according to the binomial system for South Africa; MacVicar, De Villiers, Loxton, Lambrechts, Le Roux, Merryweather, Van Rooyen, Von Harmse & Verster, 1977). The slopes and intercepts of equations for three soils (one Arcadia and two Huttons classified as indicated above) that ranged in clay content between 35 and 50 % were not used. It appears that Venter & Forbes (1983) were selective on account of these three equations' slopes, i.e. 0.35, 0.64 and 1.03 compared to slopes of only 0.66 to 0.89 of the other 11 equations. However, the slope of their equation corresponds very well with the slope of this study's equation. Both equations were derived from gravimetrically determined extractable P. According to Buys & Venter (1980) the equation for the linear relationships between ISFEI and Bray 1 reported by them was derived by Van der Merwe (1978) for a mixed batch of soils. Unfortunately, the number of soils used and their clay content are unknown. The slope of this equation which was derived from volumetrically determined extractable P values, is far larger than the slopes of the other two equations. Intercepts of these three equations ranged only between -1.22 and 1.07 (Table 4.2). Using the equation reported by Venter & Forbes (1983) and the one derived in this study (Table 4.2) Ambic 1 values were calculated for a range of selected Bray 1 values (Table 4.3).

Table 4.3 : Conversion of a selected range of Bray 1 values to Ambic 1 values using two different equations established over soils from this and another study (Table 4.2)

Bray 1 values	Ambic 1 values This study	 Venter & Forbes (1983)
mg kg^{-1}		
5	2	4
10	6	8
15	10	12
20	13	16
25	17	20
30	21	24
35	25	28
40	28	32
45	32	36
50	36	40

Ambic 1 values derived from Bray 1 values below 50 mg kg^{-1} for the two different equations (Table 4.2) corresponded reasonably well (Table 4.3). However, good relationships between Bray 1 and Ambic 1 values over soils does not justify the use of either of the two equations if slopes of the same relationship for individual soils differed significantly from each other.

4.3.2 Relationships for individual soils

Significant relationships between Ambic 1 and Bray 1 extractable P were established ($P < 0.001$ in all instances) for each locality, showing R^2-values ranging from 92 to 98 % for eight localities and from 75 to 88 % for the remaining three localities (Table 4.4). Slopes of relationships between Ambic 1 and Bray 1 extractants for soils separately varied between 0.38 and 1.08, and those between Bray 1 and Ambic 1 extractants between 0.88 and 1.98, respectively, suggesting that variation in slopes may be due to some soil properties. A comparison of slopes between localities showed significant differences ($P < 0.001$) confirming that the grouping of all soils may result in inaccurate derivations and consequently even more inaccurate P fertilizer recommendations. Using equations for the different soils reported in this study (Table 4.4) Ambic 1 values were calculated for a range of selected Bray 1 values (Table 4.5).

At the lowest Bray 1 value of 5 mg kg^{-1} the Ambic 1 values varied from -1 mg kg^{-1} (Heidelberg - N x P, Viljoenskroon and Wolmaransstad) to 4 mg kg^{-1} (Belfast and Heidelberg - Lime x P). These differences increased with higher Bray 1 values, but were not constant between localities. The Ambic 1 values at the highest Bray 1 value of 50 mg kg^{-1} ranged from 19 mg kg^{-1} (Lichtenburg) to 52 mg kg^{-1} (Athole). At a Bray 1 value of 20 mg kg^{-1}, which is regarded as more or less optimum for dryland maize production in South Africa (LNR-Instituut vir Graangewasse, 1994), differences between Ambic 1 values of between 8 and 19 will certainly result in substantial differences in P fertilizer recommendations. Considering P requirement factors (PRF's) of 5, 7 and 9 kg P ha^{-1} to increase the soil P (Bray 1) by 1 mg P kg^{-1} for soil textures of 1 to 10 % clay, 10 to 20 % clay and 21 to 35 % clay respectively, errors in derivations will be augmented when used in P recommendations.

Multiple regressions relationships between slopes of the Ambic 1 *vs.* Bray 1 relationships (Table 4.4) and selected soil properties (Table 4.6) were established over localities. Soil properties used in multiple regressions were total clay content (%), the kaolinite fraction (%), organic C, CEC, exchangeable acidity, acid and base saturation, electrical conductivity, exchangeable Ca, Mg, K, Fe, Mn, Zn and Na, as well as the free oxides of Al, Fe and Mn fractions (CBD-Al, -Fe and -Mn). However, a multiple equation which would explain variation in slopes for relationships between Ambic 1 and Bray 1 extractable P over soils sufficiently, could not be established. Consequently, simple regression relationships between slopes of the Ambic 1 and Bray 1 relationships and the same selected soil properties over localities have been established and summarized in Table 4.7.

Table 4.4 : Relationships between Ambic 1 and Bray 1 extracted P for each locality

Locality	Bray 1 values				Equation	R^2-value	*P*-value
	n	Min.	Max.	Median	Ambic 1 (mg kg^{-1}) = a + b(Bray 1; mg kg^{-1})	(%)	
Lichtenburg	224	0.1	55.9	5.2	$Y = 0.5322 + 0.3789X$	75	<0.001
Wolmaransstad	105	10.3	92.9	11.5	$Y = -3.4920 + 0.6978X$	98	<0.001
Koppies	610	0.4	111.2	20.8	$Y = -1.2764 + 0.5295X$	97	<0.001
Ventersdorp	335	1.2	113.7	3.9	$Y = -2.1184 + 0.8588X$	99	<0.001
Viljoenskroon	163	1.4	98.3	22.6	$Y = -4.0500 + 0.8810X$	86	<0.001
Stilfontein	103	0.2	133.1	22.4	$Y = -1.1920 + 0.7320X$	97	<0.001
Heidelberg (N x P)	229	6.7	103.8	22.3	$Y = -4.5100 + 0.7327X$	98	<0.001
Heidelberg (Lime xP)	126	3.1	92.4	20.8	$Y = -0.5500 + 0.9210X$	88	<0.001
Athole	114	2.1	69.2	14.8	$Y = -2.3650 + 1.0830X$	95	<0.001
Belfast	45	5.8	41.3	9.1	$Y = 1.1900 + 0.5479X$	93	<0.001
Vrede	128	4.3	103.0	22.0	$Y = -1.6810 + 0.8697X$	98	<0.001
Dirkiesdorp	148	0.5	70.6	11.1	$Y = 0.0640 + 0.6220X$	95	<0.001

Locality	Ambic 1 values				Equation	R^2-value	*P*-value
	n	Min.	Max.	Median	Bray 1 (mg kg^{-1}) = a + b(Ambic 1; mg kg^{-1})	(%)	
Lichtenburg	224	0.1	23.6	1.4	$Y = -0.2010 + 1.9760X$	75	<0.001
Wolmaransstad	105	4.9	61.2	8.6	$Y = 5.2510 + 1.4091X$	98	<0.001
Koppies	610	0.1	59.5	0.3	$Y = 2.7340 + 1.8225X$	97	<0.001
Ventersdorp	335	0.0	101.8	1.3	$Y = 2.5420 + 1.1501X$	99	<0.001
Viljoenskroon	163	0.1	98.1	13.2	$Y = 8.1110 + 0.9739X$	86	<0.001
Stilfontein	103	0.1	109.6	5.3	$Y = 2.1940 + 1.3210X$	97	<0.001
Heidelberg (N x P)	229	2.3	75.7	15.3	$Y = 6.7600 + 1.3349X$	98	<0.001
Heidelberg (Lime x P)	126	3.5	81.9	15.1	$Y = 3.6850 + 0.9514X$	88	<0.001
Athole	114	0.8	81.7	8.7	$Y = 2.8690 + 0.8761X$	95	<0.001
Belfast	45	3.7	25.8	8.0	$Y = -0.9270 + 1.6906X$	93	<0.001
Vrede	128	2.5	91.4	9.8	$Y = 2.3970 + 1.1238X$	98	<0.001
Dirkiesdorp	148	0.1	43.8	7.4	$Y = 0.6450 + 1.5315X$	95	<0.001

Table 4.5 : Conversion of selected range of Bray 1 values to Ambic 1 values using different linear equations for each locality established in this study (Table 4.4)

	Ambic 1 values											
Bray 1 values	**Lichtenburg**	**Wolmaransstad**	**Koppies**	**Ventersdorp**	**Viljoenskroon**	**Stilfontein**	**Heidelberg (N x P)**	**Heidelberg (Lime x P)**	**Athole**	**Belfast**	**Vrede**	**Dirkiesdorp**
mg kg^{-1}												
5	2	0	1	2	0	2	-1	4	3	4	3	3
10	4	3	4	6	4	6	3	9	8	7	7	6
15	6	7	7	11	9	10	6	13	14	9	11	9
20	8	10	9	15	13	13	10	18	19	12	16	13
25	10	14	12	19	18	17	14	22	25	15	20	16
30	12	17	15	24	22	21	17	27	30	18	24	19
35	14	21	17	28	26	24	21	32	35	20	29	22
40	16	24	20	32	31	28	25	36	41	23	33	25
45	18	28	23	37	35	32	28	41	46	26	37	28
50	19	31	25	41	40	35	32	46	52	29	42	31

Table 4.6 : Selected soil properties in the 0 - 150 mm soil layer at different localities extracted from Appendix 3.1

	Soil properties																
		----Exchangeable----								Organic	Acid	Base	----CBD----			1:1 Clay	Electrical
Locality	CEC	acidity	Ca	Mg	K	Fe	Mn	Zn	Na	C	---saturation---		Fe	Al	Mn	fraction^{1}	conductivity
	-----cmol$_+$ kg^{-1}-----		----mg kg^{-1}----							----%----							---m S m^{-1}--
Lichtenburg	19.960	0.057	3867	49	57	7	2	5.18	5	0.900	0.3	99.7	0.346	0.050	0.039	7	48.6
Wolmaransstad	2.549	0.047	314	104	87	20	8	1.66	13	0.180	1.7	98.3	0.821	0.056	0.026	21	9.6
Koppies	27.782	0.027	3907	797	322	7	2	16.0	195	0.795	0.1	99.9	0.264	0.082	0.047	7	109.7
Ventersdorp	4.280^{2}	1.890^{2}	227^{2}	69^{2}	48^{2}	73	31	0.8	2^{2}	0.322	0.1	99.9	2.420	0.139	0.087	42	6.0
Viljoenskroon	1.584	0.095	196	47	47	65	5	2.25	1	0.154	6.0	94.0	0.626	0.068	0.008	28	4.5
Stilfontein	3.321	0.038	427	83	179	22	23	2.11	1	0.589	1.1	98.9	2.810	0.110	0.064	52	13.1
Heidelberg (N x P)	3.312	0.068	451	90	71	56	12	3.04	12	0.510	2.5	97.5	0.989	0.140	0.018	13	16.9
Heidelberg (Lime x P)	2.695	0.082	283	110	118	43	24	2.71	1	0.435	2.5	97.5	1.670	0.073	0.028	21	27.2
Athole	2.194	0.817	181	45	38	137	5	2.74	1	1.733	37.2	62.8	4.600	1.571	0.004	27	7.8
Belfast	7.000	0.041	1096	162	50	115	7	1.63	4	0.953	0.6	99.4	0.532	0.140	0.002	14	21.5
Vrede	4.947	0.081	675	154	85	313	15	2.61	1	1.092	1.6	98.4	0.447	0.080	0.024	21	16.8
Dirkiesdorp	5.408	0.171	870	96	35	74	4	3.84	1	1.568	3.2	96.8	3.350	0.772	0.005	66	26.4

[1] Total clay content indicated in Table 3.6 and Appendix 3.1; [2] Composition of data used for the Ventersdorp locality is explained in Table 3.14

Table 4.7 : Relationships between slopes for the Ambic 1 *vs*. Bray 1 relationships and selected soil properties over localities

X = Soil poperties		Equation	R^2- value	*P*-value	
		Y = slope of Ambic 1 and Bray 1 relationship	%	intercept	slope
Exchangeable Ca	(mg kg^{-1})	$Y = (3.41339X^{-0.24677})$	80	0.0006	0.0001
CEC	(cmol$_c$ kg^{-1})	$Y = (1.09584X^{-0.27933})$	68	ns	0.0010
Exchangeable Fe	(mg kg^{-1})	$Y = (1 / (1.16854 + 7.36446 / X))$	60	0.0000	0.0029
CBD-Mn	(%)	$Y = (0.68883 - 0.01223 (\ln X))$	60	0.0078	ns
1:1 Clay fraction	(%)	$Y = (1 / (0.97360 + 8.34097 / X))$	58	0.0001	0.0038
Exchangeable Mn	(mg kg^{-1})	$Y = (1 / (1.06818 + 2.18250 / X))$	57	0.0000	0.0043
Acid saturation	(%)	$Y = (0.60323 + 0.08497 (\ln X))$	45	0.0000	0.0164
CBD-Fe	(%)	$Y = (1 / (1.09918 + 0.26642 / X))$	41	0.0001	0.0238
Exchangeable acidity	(cmol$_+$ kg^{-1})	$Y = (1.91350 - 0.01148 / X)$	39	0.0000	0.0302
Base saturation	(%)	$Y = (1.84246 - 0.01160X)$	37	0.0024	0.0353
CBD-Al	(%)	$Y = (0.68665 + 0.18935X)$	19	0.0000	ns
Exchangeable Mg	(mg kg^{-1})	$Y = (1.16638 - 0.09285 (\ln X))$	13	0.0075	ns
Clay	(%)	$Y = (1 / (1.74092 - 4.78380 / X))$	8	0.0003	ns
Organic C	(%)	$Y = (1 / (1.61688 - 0.06808 / X))$	8	0.0000	ns
		Y = slope of Bray 1 and Ambic 1 relationship			
Exchangeable Ca	(mg kg^{-1})	$Y = (-0.59493 + 0.30546 (\ln X))$	83	ns	0.0000
CEC	(cmol$_c$ kg^{-1})	$Y = (0.79750 + 0.35482 (\ln X))$	74	0.0000	0.0003
CBD-Mn	(%)	$Y = (1.40147X^{0.01796})$	72	ns	ns
Exchangeable Fe	(mg kg^{-1})	$Y = (1.13623 + 5.21865 / X)$	54	0.0000	0.0065
1:1 Clay fraction	(%)	$Y = (0.99925 + 5.89077 / X)$	52	0.0000	0.0082
Exchangeable Mn	(mg kg^{-1})	$Y = (1.07225 + 1.50732 / X)$	49	0.0000	0.0116
CBD-Fe	(%)	$Y = (1.07309 + 0.19896 / X)$	41	0.0000	0.0246
Exchangeable acidity	(cmol$_+$ kg^{-1})	$Y = \exp (0.02458 + 0.01574 / X)$	41	ns	0.0250
Acid saturation	(%)	$Y = (1.33043 X^{-0.09224})$	38	0.0011	0.0315
Base saturation	(%)	$Y = (1 / (1.94491 - 0.01212X))$	37	0.0023	0.0362
Exchangeable Mg	(mg kg^{-1})	$Y = (0.64818X^{0.15147})$	20	ns	ns
CBD-Al	(%)	$Y = (1 / (0.74198 + 0.18270X))$	16	0.0000	ns
Clay	(%)	$Y = (1.59991 - 4.39934 / X)$	12	0.0001	ns
Organic C	(%)	$Y = (1.47482 - 0.05765 / X)$	10	0.0000	ns

Exchangeable Ca, CEC, exchangeable Fe, CBD-Mn, the 1:1 clay fraction (kaolinite) and exchangeable Mn explained most of the variation in slopes for relationships between Ambic 1 (Y) *vs.* Bray 1 (X) extractable P over soils, R^2-values of 80, 68, 60, 60, 58 and 57 %, respectively (Table 4.7). The remaining soil properties, i.e. acid saturation, CDB-Fe, exchangeable acidity, base saturation, CDB-Al, exchangeable Mg, clay content and organic C, explained variation of between 45 and 8 %, thus having a much smaller effect on these slope differences between soils. Exchangeable Ca, CEC, CBD-Mn, exchangeable Fe and the 1:1 clay fraction (kaolinite) explained most of the variation in slopes for relationships between Bray 1 (Y) *vs.*

Ambic 1 (X) extractable P over soils, with R^2-values of 83, 74, 72, 54 and 52 %, respectively. The remaining properties, i.e. exchangeable Mn, CDB-Fe, exchangeable acidity, acid saturation, base saturation, exchangeable Mg, CBD-Al, clay content and organic C, explained variation of between 49 and 10 %, respectively. In both instances the regression equation obtained with CBD-Mn were not significant at a 95 % confidence level.

It is evident that exchangeable Ca concentrations explained variation the best and can therefore be used for the prediction of slopes in comparisons between Ambic 1 and Bray 1 extractable P. Due to expected soil variation over short distances it may not be absolutely justifiable to relate soil properties obtained from profile pits with extractable P data obtained from plots near to the pits. Nevertheless, these regression analyses showed that several soil properties influence the efficacy of both extractants. These findings warrant further investigation before universal equations can be established for the conversion of Ambic 1 to Bray 1 extractable P values and *vice versa.*

4.4 Conclusion

The use of simple regression equations derived from relationships between Ambic 1 and Bray 1 extractions over soils may result in a very high degree of inaccuracy, with an even higher degree of inaccuracy for P fertilizer recommendations. Soil properties had a significant influence on the efficacy of the two extractants. Slopes of relationships between Ambic 1 (Y) and Bray 1 (X) could thus far be predicted by using only exchangeable Ca in simple regression relationships. Universal equations for the conversion of Ambic 1 to Bray 1 extractable P values and *vice versa* should, according to simple regressions, at least include soil properties such as exchangeable Ca, acid saturation, CEC, the kaolinite clay content, and possibly also exchangeable acidity, base saturation and Fe content.

CHAPTER 5

RELATIONSHIPS BETWEEN EXTRACTABLE SOIL PHOSPHORUS AND FERTILIZER PHOSPHORUS APPLICATION

5.1 Introduction

The amount of fertilizer P required to increase extractable soil P is dependant on several soil factors which *inter alia* include Al and Fe hydrous oxides, the type and amount of clay, reactive $CaCO_3$ and organic matter. By the use of appropriate soil P tests, it is possible to determine fertilizer P requirements to reach and maintain optimal soil P levels for crop production goals (Indiati et al., 1999). Goswami et al. (1990) stressed the fact that the crop requirement for fertilizer P should take the soil P supply and its contribution, and the efficiency of P fertilizer in a given soil-climate environment, into account. For example, for a similar yield response of wheat to P fertilization, 53 kg P ha^{-1} would be required on a high P-fixing soil as compared to 26 kg P ha^{-1} on a low P-fixing soil. On another soil, in order to obtain a yield response of 1 t ha^{-1}, 18 kg P ha^{-1} was required on a soil having 15 kg available P ha^{-1}, compared to 35 kg P ha^{-1} on a soil with 7.5 kg available P ha^{-1} (Olsen). Mengel & Kirby (1987) suggested that if the quantity of available soil P is in a normal range, the rate of P application required should correspond to the amount of P removed by the crop. As some of the labile P is rendered immobile, P application rates should be about 10 to 50 % higher than the quantity of P taken up by the crop.

Several authors have attempted to relate soil properties to the effectiveness of fertilizer P, i.e. Moorhead & McLean (1985), Indiati et al. (1991), Moughli et al. (1993), Indiati & Sharpley (1995) and Indiati et al. (1999). However, some researchers used clay content to predict the quantity of P fertilizer needed to raise soil P test in a variety of soils (Johnston et al., 1991; Cox, 1994). Farina et al. (1993) did indirectly the same by relating the quantity of P fertilizer needed to raise soil P test to sample density and in turn the sample density to clay content (Johnston, Farina & Lawrence, 1987). According to Farina et al. (1993) optimum soil P test values for maize production increase with increasing sand content, but the amount of fertilizer required to increase soil test by a single unit is lower for sandy soils compared to clayey soils. In clayey soils a lower percentage of P is removed by the P test than in the case of sandy soils. Relationships between P measured and added were found to be near linear (Farina & Mapham, 1973; Johnston et al., 1991; Landman, 1995) so that linear regression functions could be fitted to data of this nature. This implies that the slope of such a function can be used to calculate the P requirement factor

(PRF) of a soil (Johnston et al., 1991; LNR-Instituut vir Graangewasse, 1994), i.e. the quantity of P fertilizer that must be applied to raise the soil P test value by one unit.

The objective of this study was to establish through linear regression analyses PRF's for individual localities by relating extractable P concentrations (mg kg^{-1}) and quantities (kg ha^{-1}) as determined by either the Ambic 1 or Bray 1 extractants in soil volumes over rows as well as in total soil volumes to P rates (kg ha^{-1}). In addition the objective was to relate differences in these PRF's between soils to soil properties which can be used in fertilizer recommendations.

5.2 Procedure

Some general information on the soil sampling and analyses for soil phosphorus contents are presented in Section 3.6.1. As was previously described P contents of soil volumes over and between the rows were determined separately for all trials except at Dirkiesdorp. All these samples were analyzed for extractable P (Ambic 1) concentrations. Only data from the first growing seasons at all trials was intended to be used in relationships between extractable soil P values and fertilizer P applications. However, not all data from the first growing seasons was suitable and therefore those from the second or other seasons was used where applicable. As explained in Table 5.1 data from the first season was used at seven localities (Lichtenburg, Koppies, Ventersdorp, Stilfontein and Belfast), from the second season at four localities (Wolmaransstad, Heidelberg - Lime x P, Athole and Vrede) and from the third and fifth season at one locality, respectively (Dirkiesdorp and Heidelberg - N x P). At the Viljoenskroon locality data from various seasons between 1993/94 and 1999/00 was used.

The concentrations (mg kg^{-1}) of extractable P that were measured within the soil volumes over and between the rows were converted to quantities (kg ha^{-1}) by taking the actual bulk densities (Table 3.6) into account. Both the weighted mean concentrations and quantities of extractable P in the total soil volumes were then calculated. Soil volumes at 0.90 m (Koppies, Athole, Belfast and Vrede), 1.50 m (Viljoenskroon, Stilfontein and Heidelberg) and 2.24 m (Lichtenburg, Wolmaransstad, Koppies and Ventersburg) row spacings represented 33, 20 and 13.4 % of the volumes over rows and 67, 80 and 86.6 % of the total soil volumes, respectively.

Table 5.1 : Relevant information on the accumulation of data used for the determination of relationships between extractable and applied P

Localities	Comment
Lichtenburg	Data from the first growing season, i.e. 1989/90, for both soil volumes was used for the determination of soil reactions.
Wolmaransstad	The P enriched zones were not reflected in analysis of the first growing season, i.e. 1991/92, due to incorrect sampling. Data from the second season, i.e. 1992/93, for both soil volumes was therefore used. Soil reactions were determined at all P rates, but only for the 80 and 120 kg N ha^{-1} treatments.
Koppies (2.24 m)	Data from the first growing season, i.e. 1998/99, for both soil volumes was used.
Ventersdorp	Data from the first growing season, i.e. 2001/02, for both soil volumes was used.
Viljoenskroon	Extractable P in both soil volumes varied between seasons and for this reason data from the 1993/94 until the 1999/00 season was used in soil volumes over rows and data from the 1994/95 until the 1999/00 season for that of the soil volume between rows. Variation in extractable residual P is attributed to human or experimental error as rows were not kept exactly on the same spot each season.
Stilfontein (N x P)	Data from the first growing season, i.e. 1998/99, for both soil volumes was used. However, data for the highest P rate, i.e. 50 kg ha^{-1}, was excluded from the determination as extractable P values were lower than at 40 kg P ha^{-1}.
Stilfontein (P)	Data from the first growing season, i.e. 1998/99, for the soil volume over rows was used. Extractable P values for the control treatment was used as a indication of between row volumes.
Heidelberg (N x P)	Soil samples for the determination of extractable P for soil volumes between rows was not determined during the first season, i.e. 1991/92. Extractable P values for both soil volumes from the second until the fourth season varied a lot, resulting in poor or unreliable relationships. Results from the fifth until the seventh season was more constant and therefore extractable P data from the fifth season, i.e. 1995/96, was used for both soil volumes. Variation in extractable P values between seasons for the earlier seasons was due to deviation in the application of the sampling technique and variation in positioning of maize rows.
Heidelberg (Lime x P)	The first season, i.e. 1991/92, soil samples were only collected between maize rows and therefore data from the second season was used. Soil samples from only the volume over rows were collected throughout the course of the trial and therefore extractable P values for the control treatment was used as an indication of P levels for between row volumes.
Athole	Due to deviation in the application of the soil sampling technique followed during the first season, i.e. 1996/97, enriched zones over maize rows were not accurately reflected, therefore data from the second season was used. Soil samples from only the soil volume over rows were collected throughout the course of the trial and therefore extractable P values for the control treatment was used as an indication of P levels for between row volumes.
Belfast	Data from the first growing season, i.e. 1996/97, for the soil volume over rows was used. Soil samples from only the soil volume over rows were collected throughout the course of the trial and therefore extractable P values for the control treatment was used as an indication of P levels for between row volumes.
Vrede	Due to deviation in the application of the soil sampling technique followed during the first season, i.e. 1996/97, enriched zones over maize rows were not accurately reflected, therefore data from the second season was used. Soil samples from only the soil volume over rows were collected throughout the course of the trial and therefore extractable P values for the control treatment was used as an indication of P levels for between row volumes.
Koppies (0.90 m)	Data from the first growing season, i.e. 1998/99, for both soil volumes was used.
Dirkiesdorp	Data from the first two growing seasons was lost during rationalisation of the ARC-Grain Crops Institute and can therefore not be accounted for. Data from the third season, i.e 1998/99, was used for the determination of soil reactions.

Calculations were done on the Ambic 1 values only, followed by analyses of variance. These mean values were transposed to equivalent Bray 1 values according to the established relationships between Ambic 1 and Bray 1 for each locality (Table 4.4).

Simple linear regression analyses were done between either extractable P concentrations or quantities and applied fertilizer P values for all trials pooled and individually followed by calculations for PRF's from the slopes. The PRF's were then related to different soil properties by simple and multiple regression analyses.

5.3 Results and discussion

5.3.1 Relationships over soils

Effects of P applications on extractable P for different soil volumes over all localities are presented as relationships in Figure 5.1 for Ambic 1 and Figure 5.2 for Bray 1. In general Bray 1 explained more variation than Ambic 1, i.e. R^2-values of 52, 54, 24 and 18 % for Bray 1 compared to 49, 26, 15 and 10 % for Ambic 1. The R^2-values for these relationships were much higher in the soil volumes over the rows than in the total soil volumes due to band placement of P fertilizer. However, even for the soil volumes over the rows the R^2-values were unacceptable low, explaining less than 55 % of the variation. This implies that PRF's calculated from the slopes of these relationships over soils are not applicable to any particular soil. Consequently these relationships were drawn for each soil.

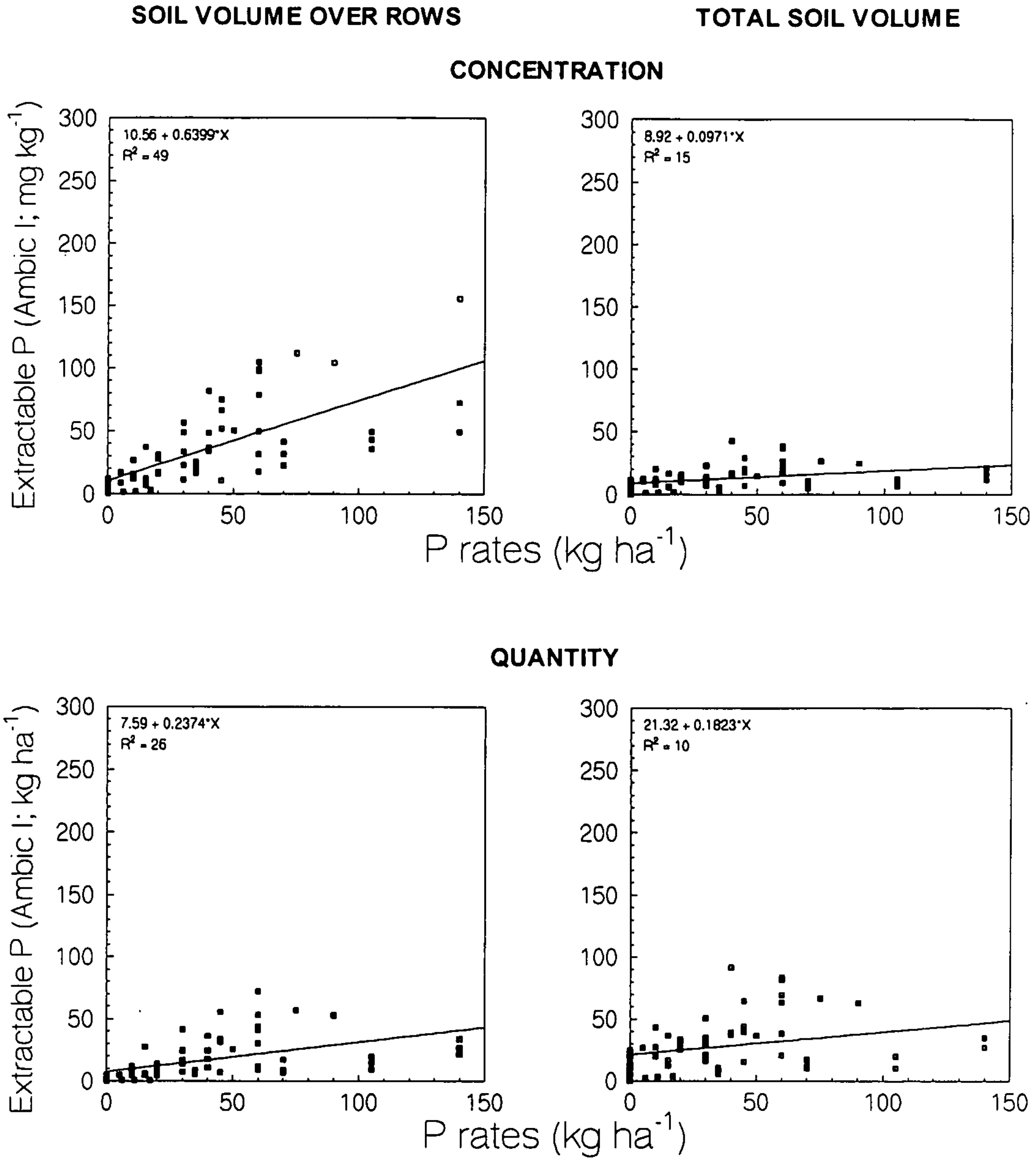


Figure 5.1 : Effects of P rates on extractable P (Ambic 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm over localities (n = 68).

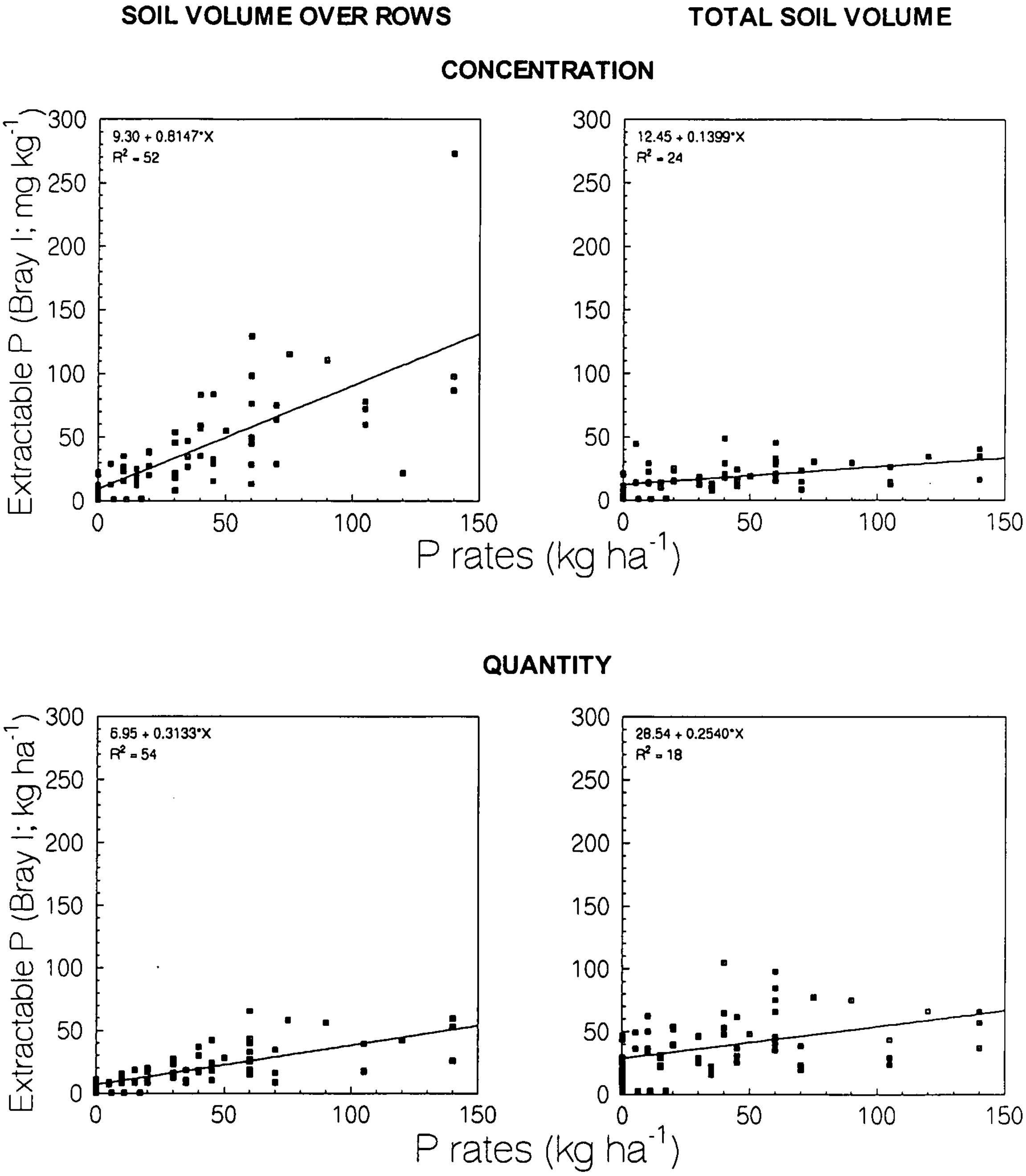


Figure 5.2 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm over localities (n = 72).

5.3.2 Relationships for individual soils

Effects of P applications on extractable P for different soil volumes are presented as relationships in Figures 5.3 to 5.16 for the different localities.

Relationships for all localities (Figures 5.4 to 5.16) are according to the Bray 1 extractant, except those for Lichtenburg (Figure 5.3) that are according to the Ambic 1 extractant. The reason for this is that the Ambic 1 extraction method is more suitable than the Bray 1 method in alkaline soil (Van der Merwe et al., 1984) at Lichtenburg (Appendix 3.1). However, similar relationships were established for Lichtenburg using Bray 1 values and for the other localities using Ambic 1 values which are only presented as equations in Table 5.2.

Large differences in the slopes of the linear regression equations were shown in Figures 5.3 to 5.16 and Table 5.2. In general the slopes differed between soils for a specific scenario (Figures 5.3 to 5.16), but also between scenarios for a specific soil as clearly illustrated at Viljoenskroon (Figure 5.7) for example. The PRF's (1/slope) that were calculated from the slopes of the linear regression equations between extractable P and applied P showed large differences in PRF's (Table 5.3). For example the quantity of fertilizer P needed to raise the concentration of Ambic 1 extractable P by one unit in the total soil volume varied from 1.6 kg ha^{-1} at Heidelberg (Lime x P) to 23.8 kg ha^{-1} at Lichtenburg. Several other such examples can be highlighted in this table. Therefore, the PRF's given in Table 5.3 clearly show that the studied soils differed in response to applied P. These differences in soil reactions to applied P should be accommodated in fertilizer recommendations in some or other way.

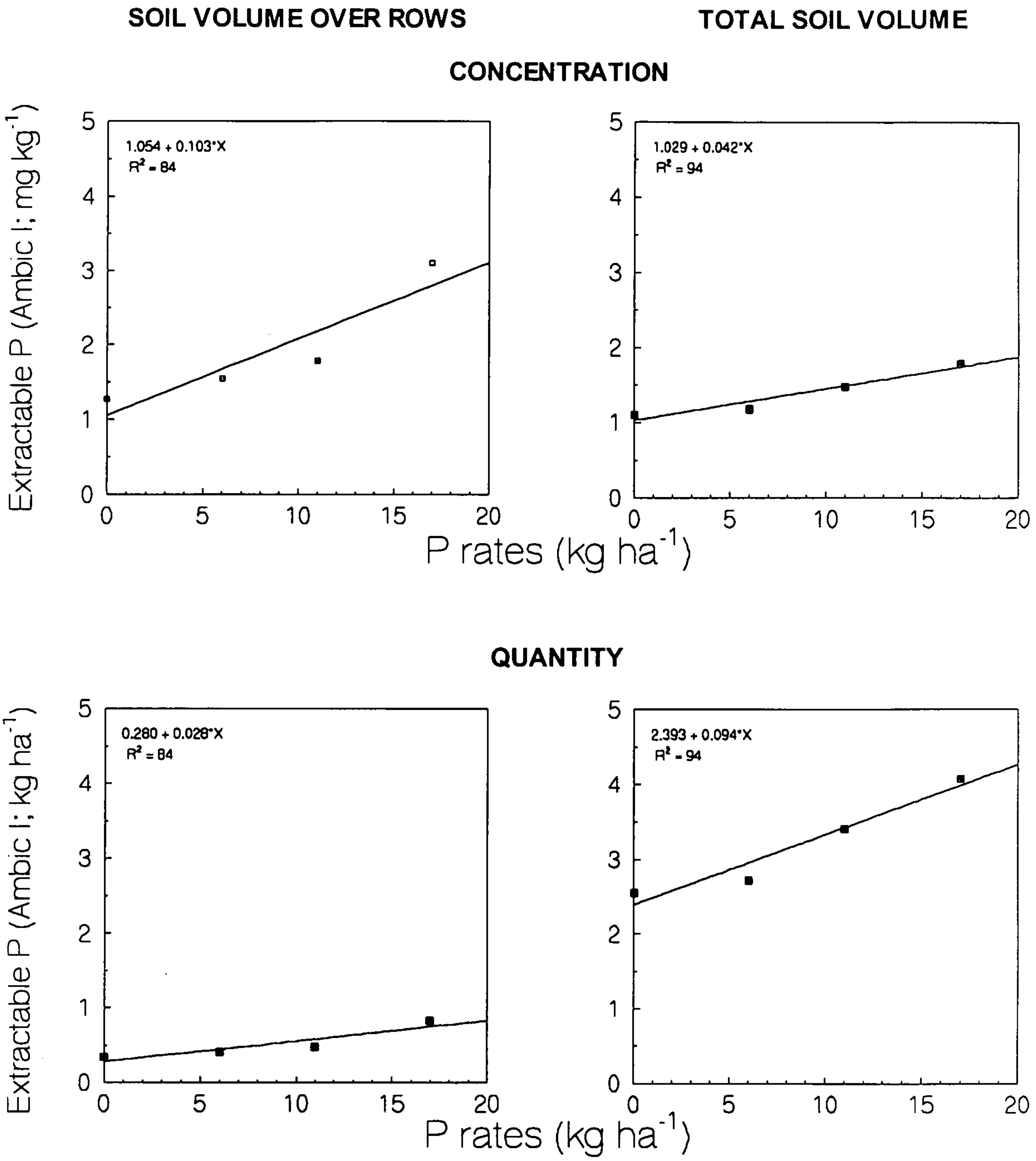


Figure 5.3 : Effects of P rates on extractable P (Ambic 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Lichtenburg (n = 4, consisting of 16 data points each).

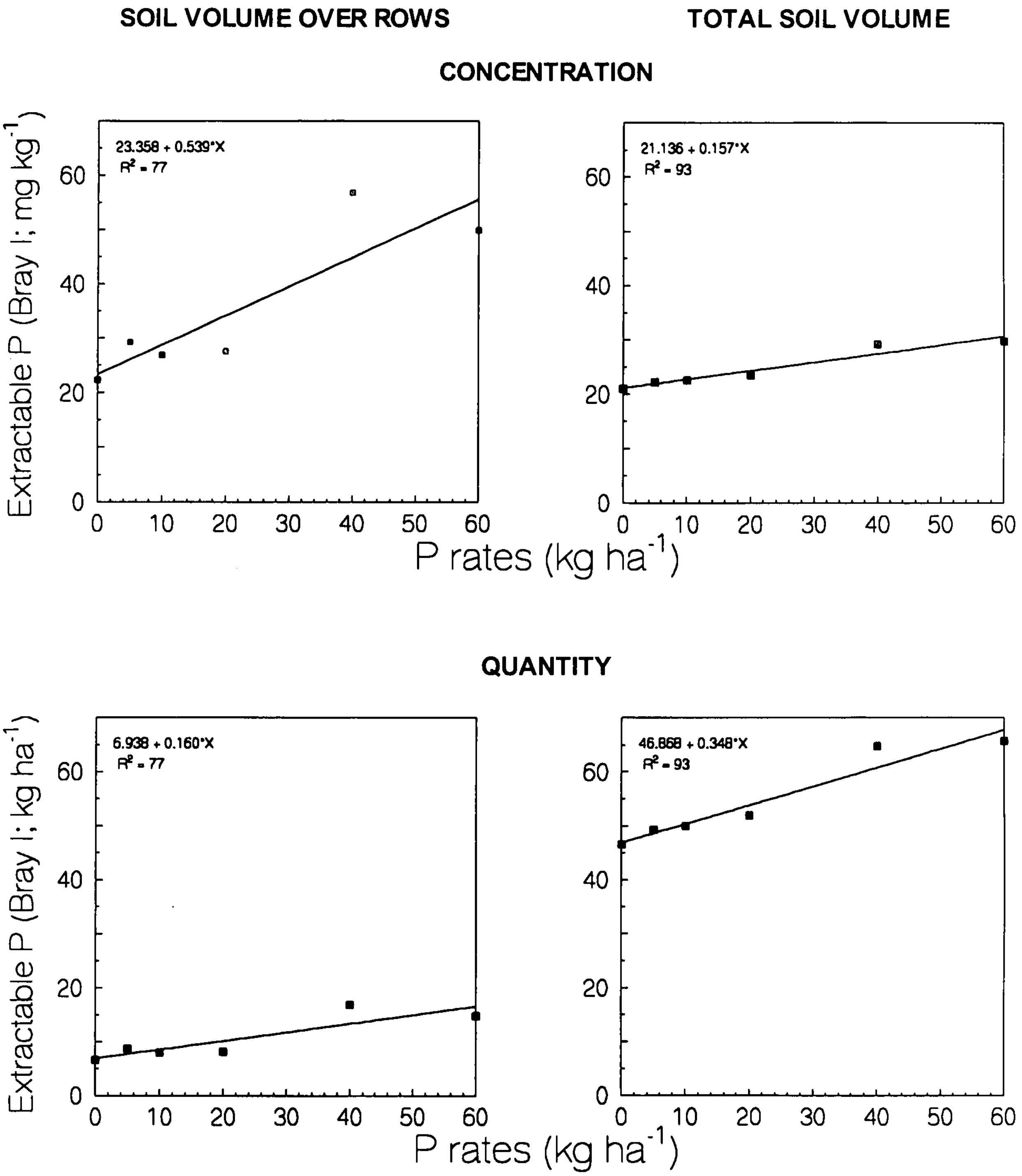


Figure 5.4 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Wolmaransstad (n = 6, consisting of 6 data points each).

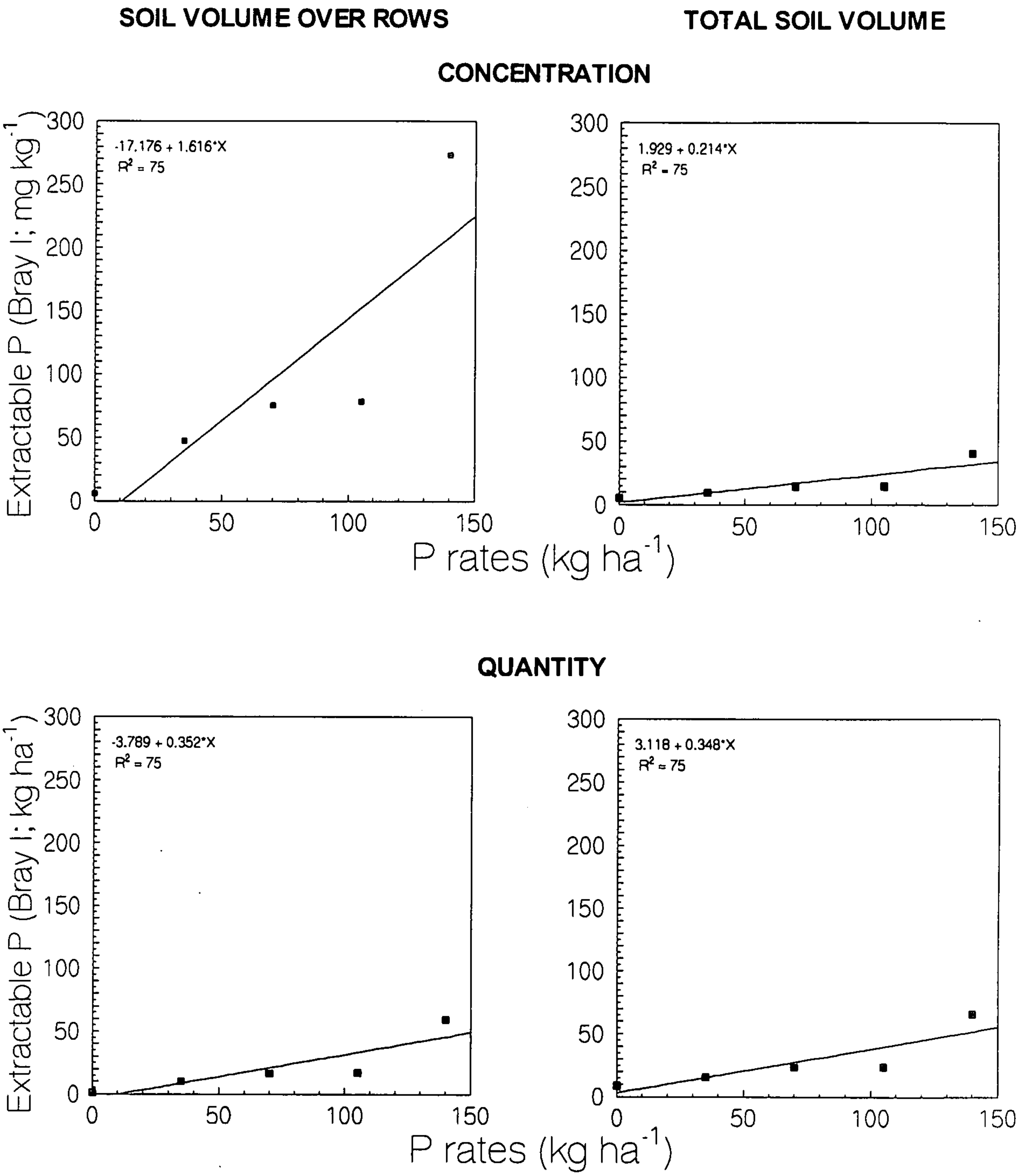


Figure 5.5 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Koppies (2.24 m trial; n = 5, consisting of 10 data points each).

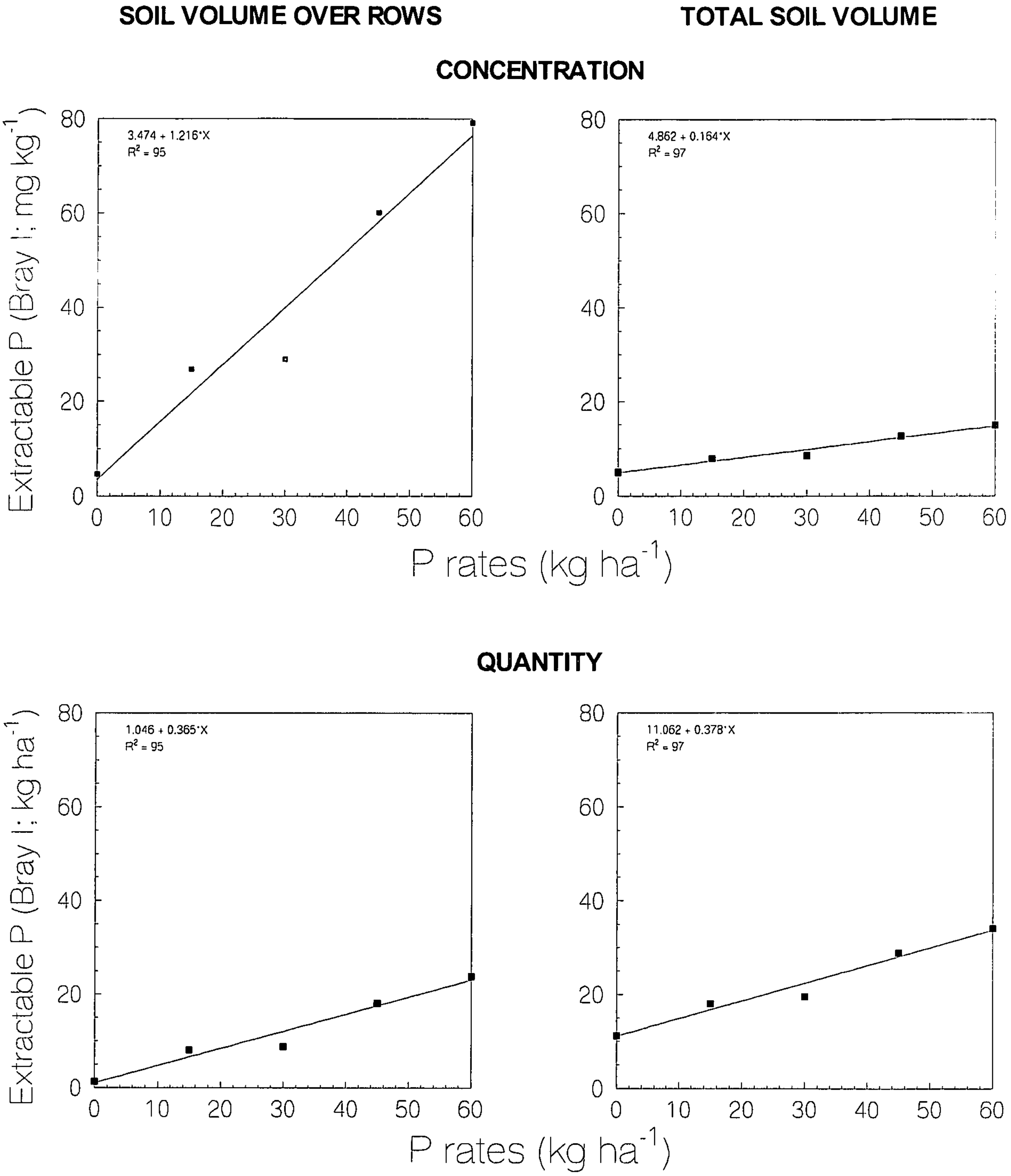


Figure 5.6 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Ventersdorp (n = 5, consisting of 10 data points each).

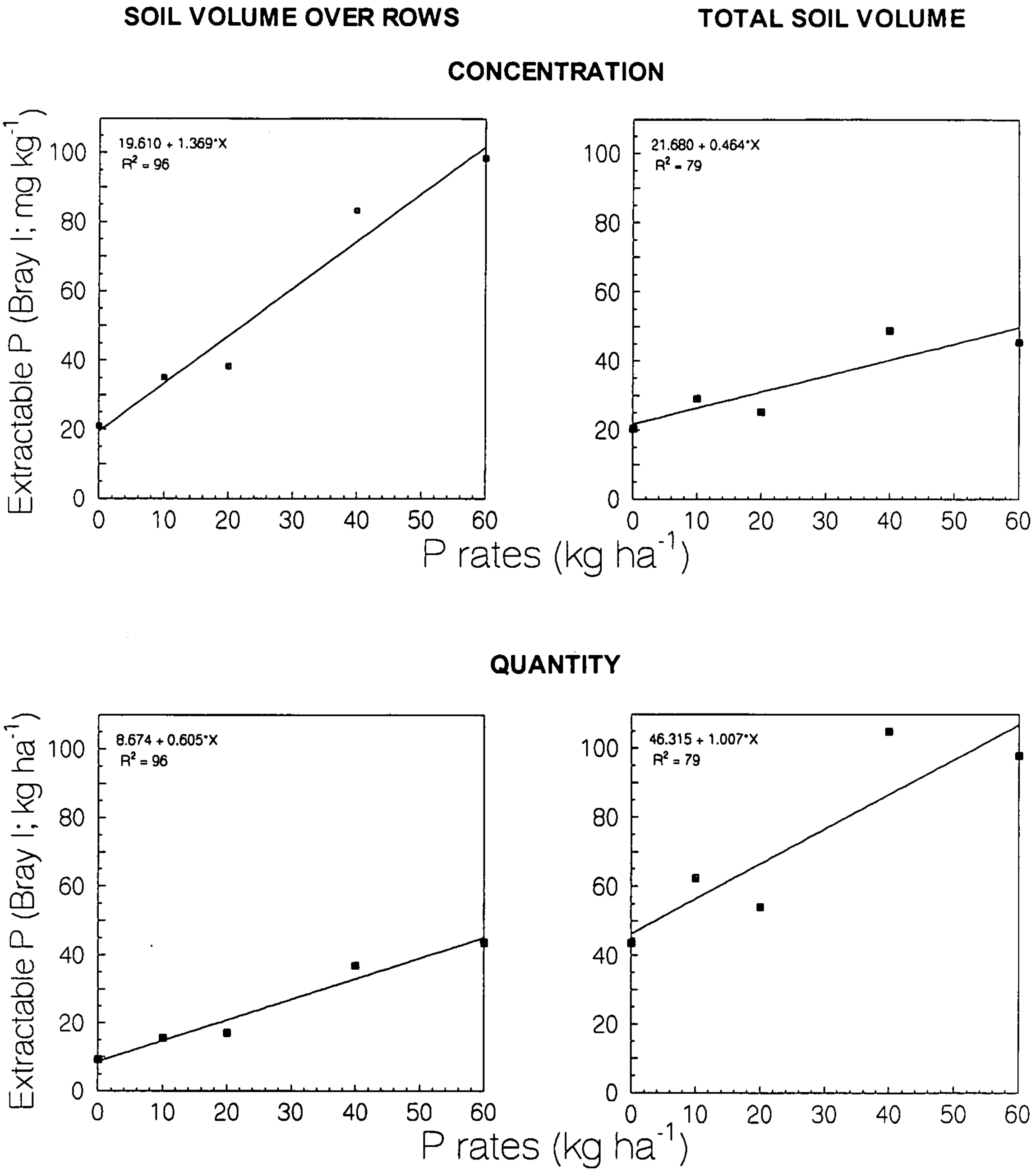


Figure 5.7 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Viljoenskroon (n = 5, consisting of 21 and 18 data points each for soil volumes over and between rows, respectively).

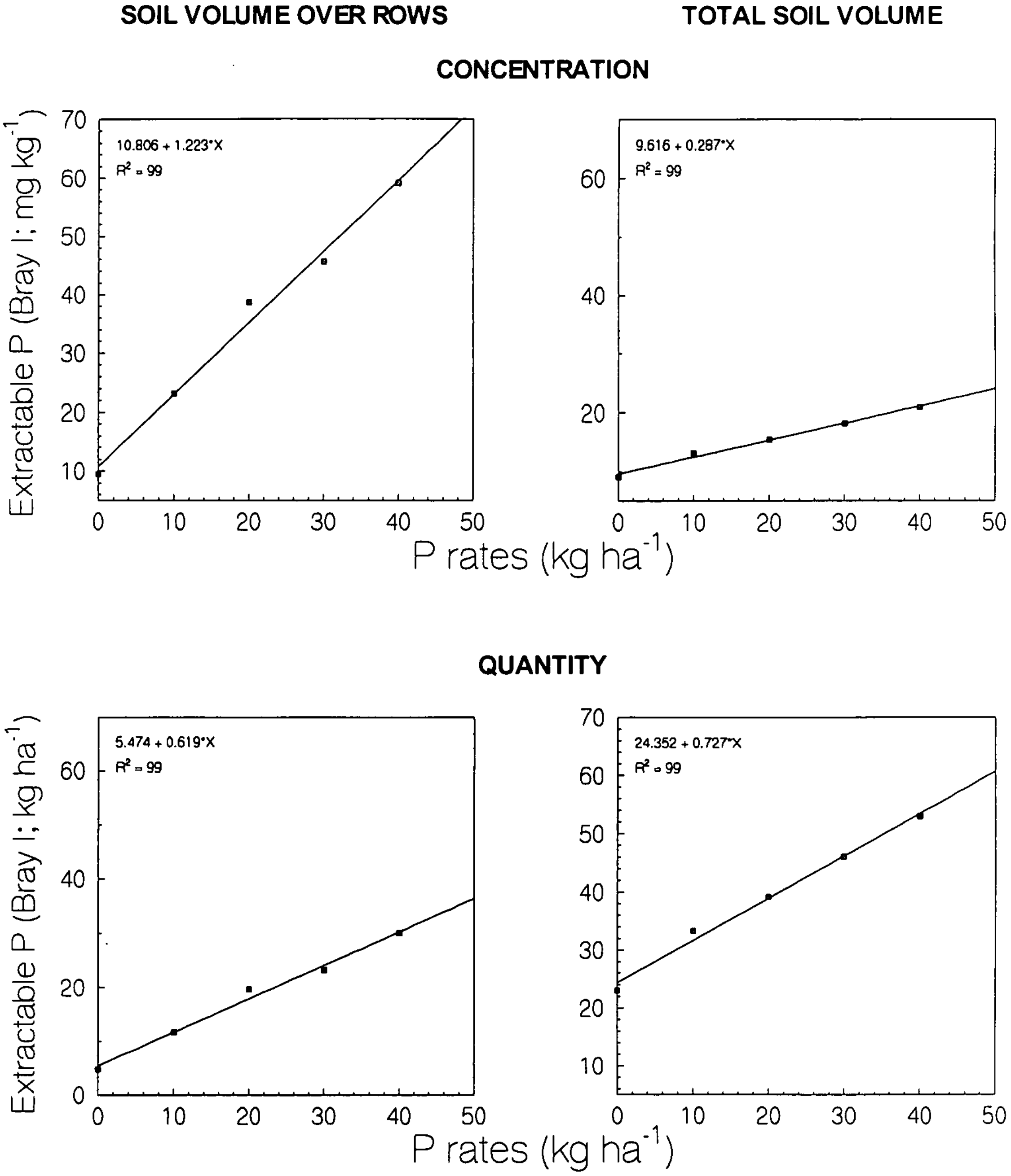


Figure 5.8 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Stilfontein (N x P trial; n = 5, consisting of 12 data points each).

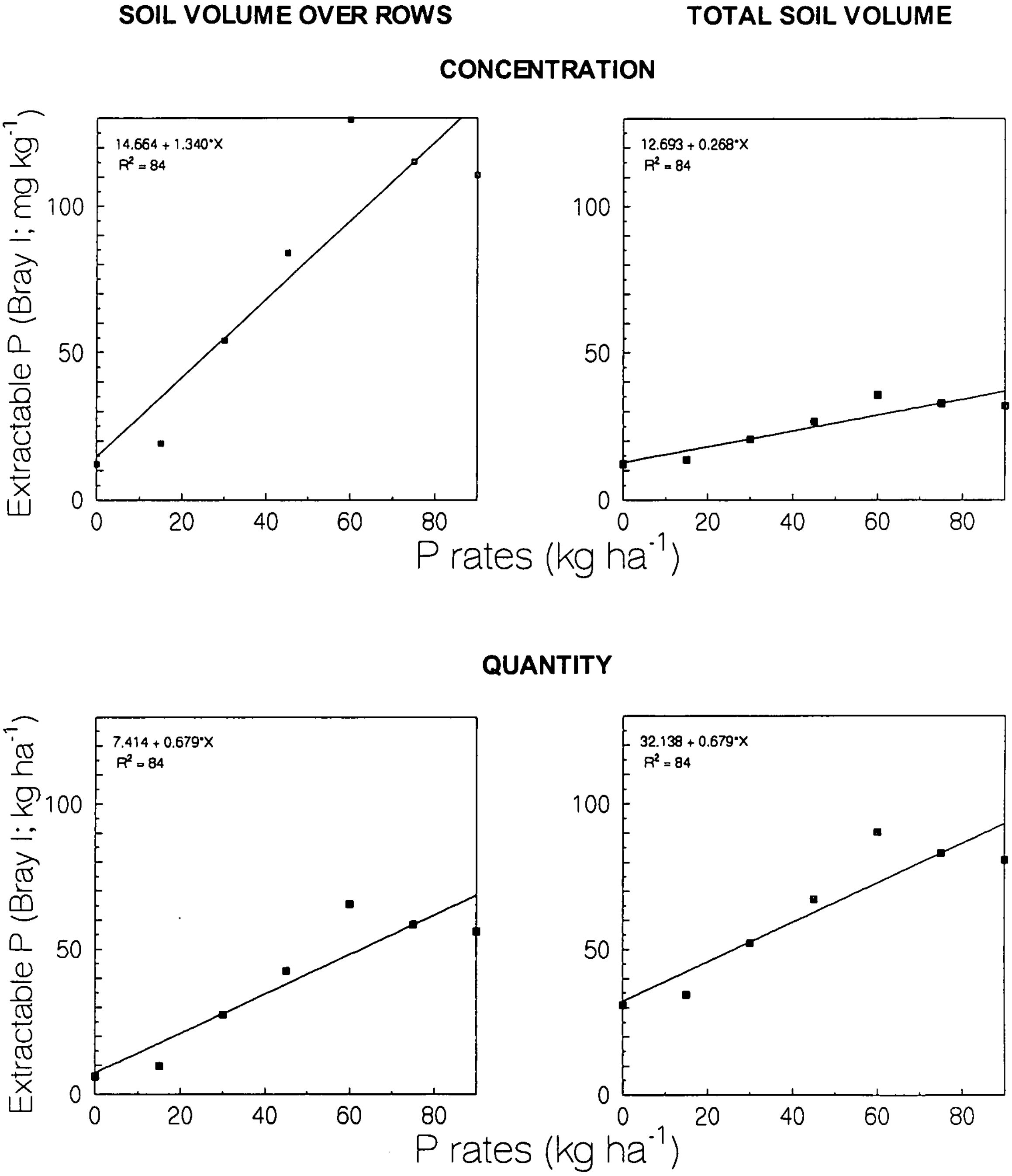


Figure 5.9 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Stilfontein (P source trial; n = 7, consisting of 2 data points each).

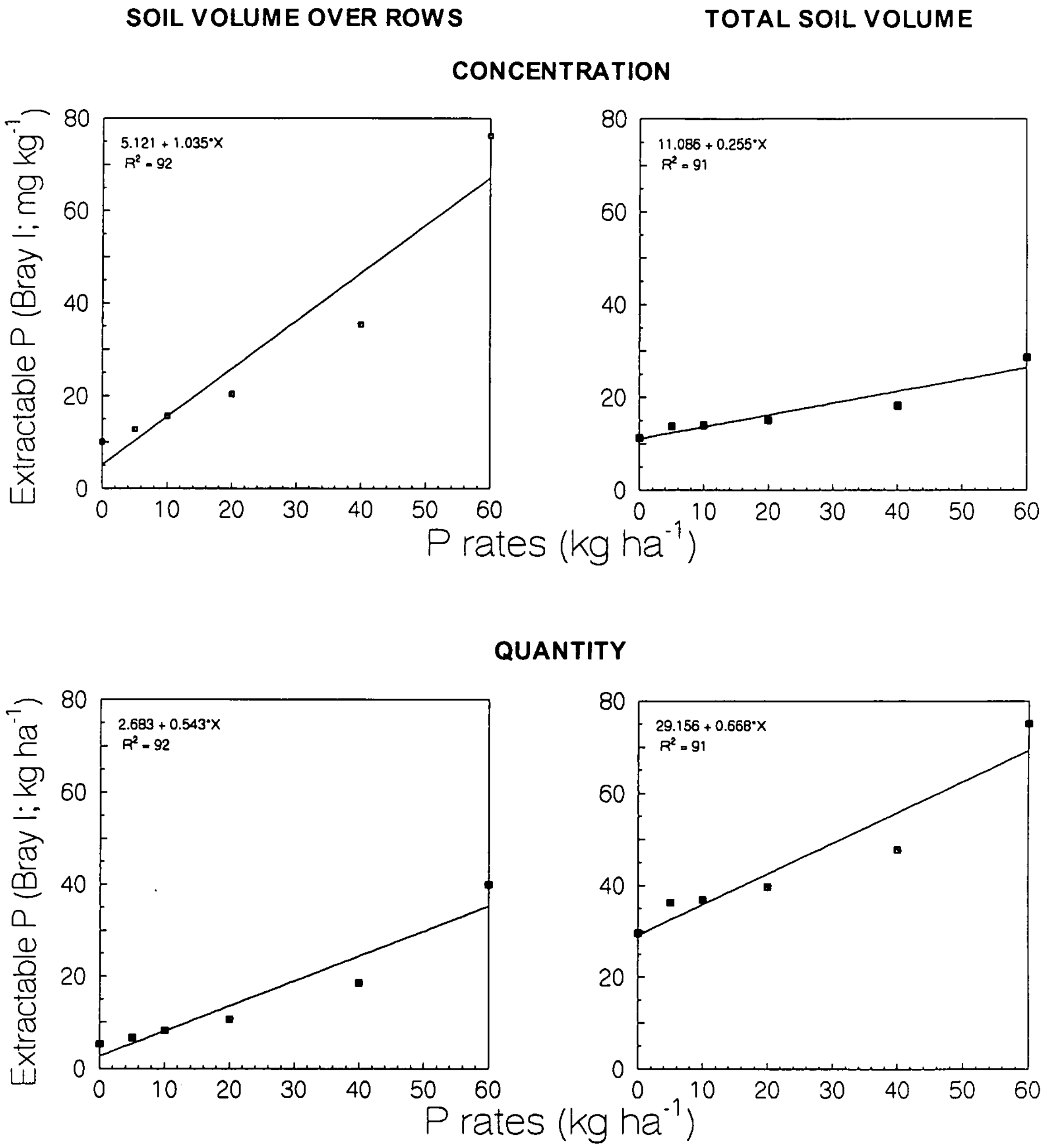


Figure 5.10 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Heidelberg (N x P trial; n = 6, consisting of 9 data points each).

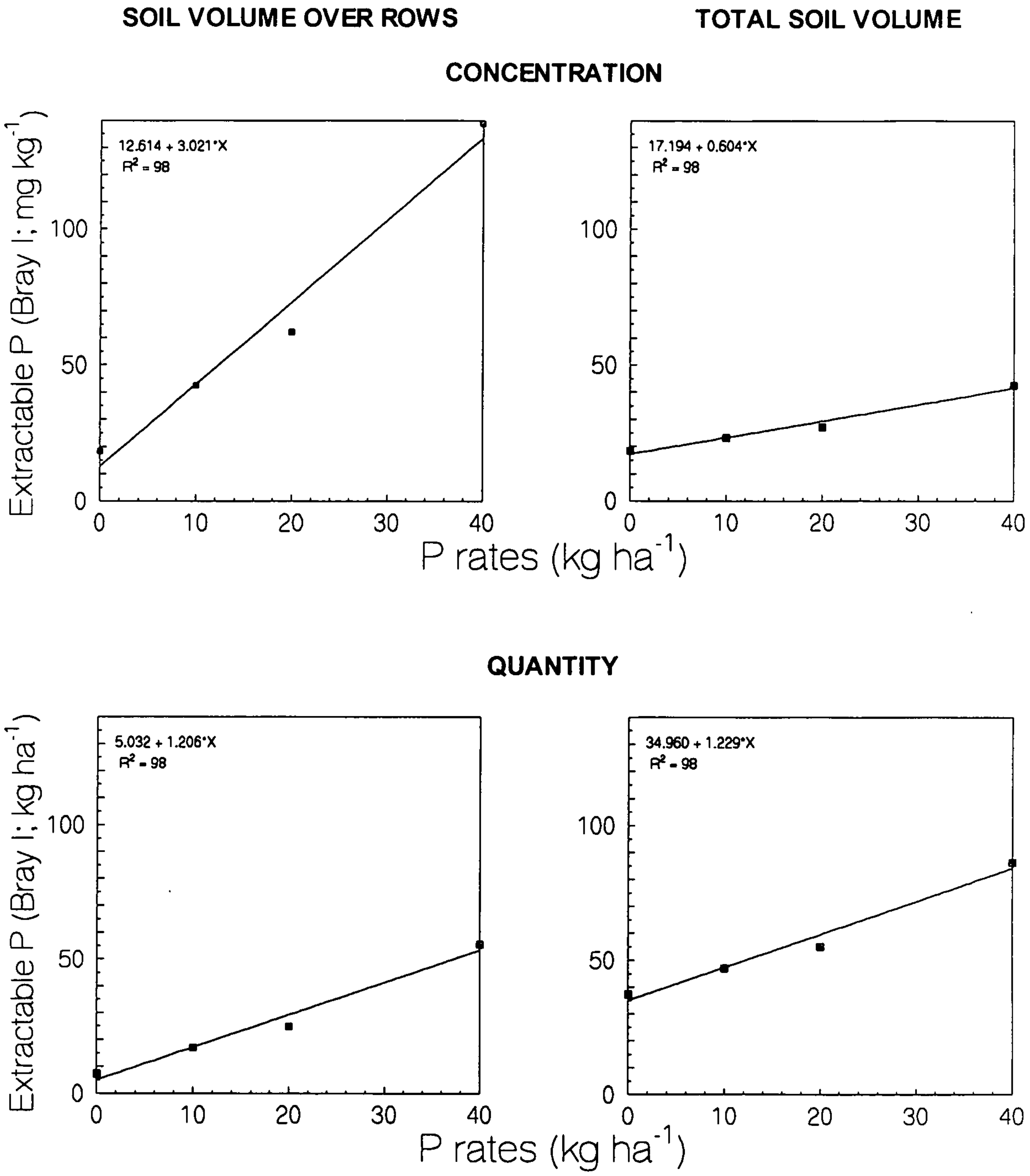


Figure 5.11 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Heidelberg (Lime x P trial; n = 4, consisting of 20 data points each).

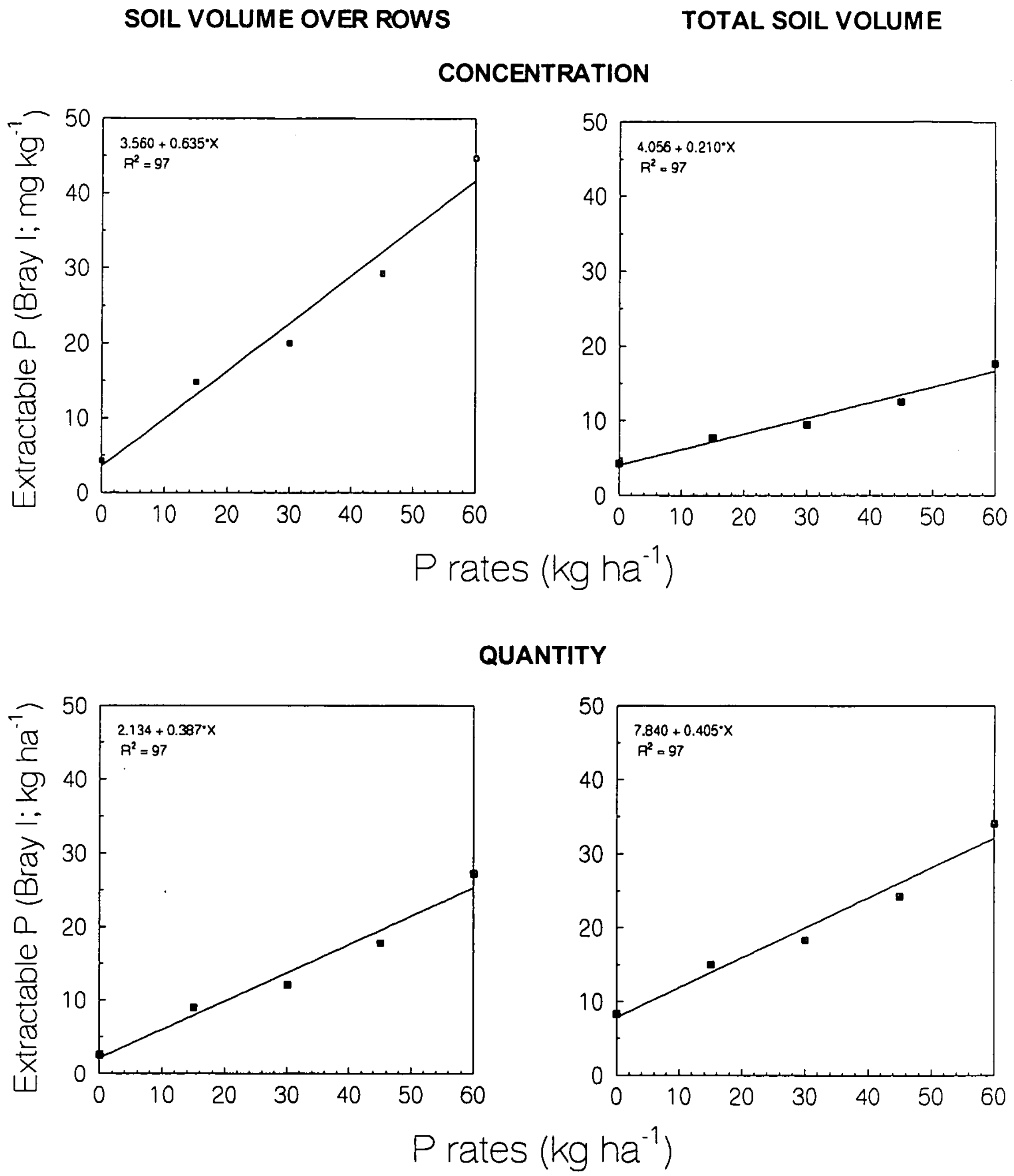
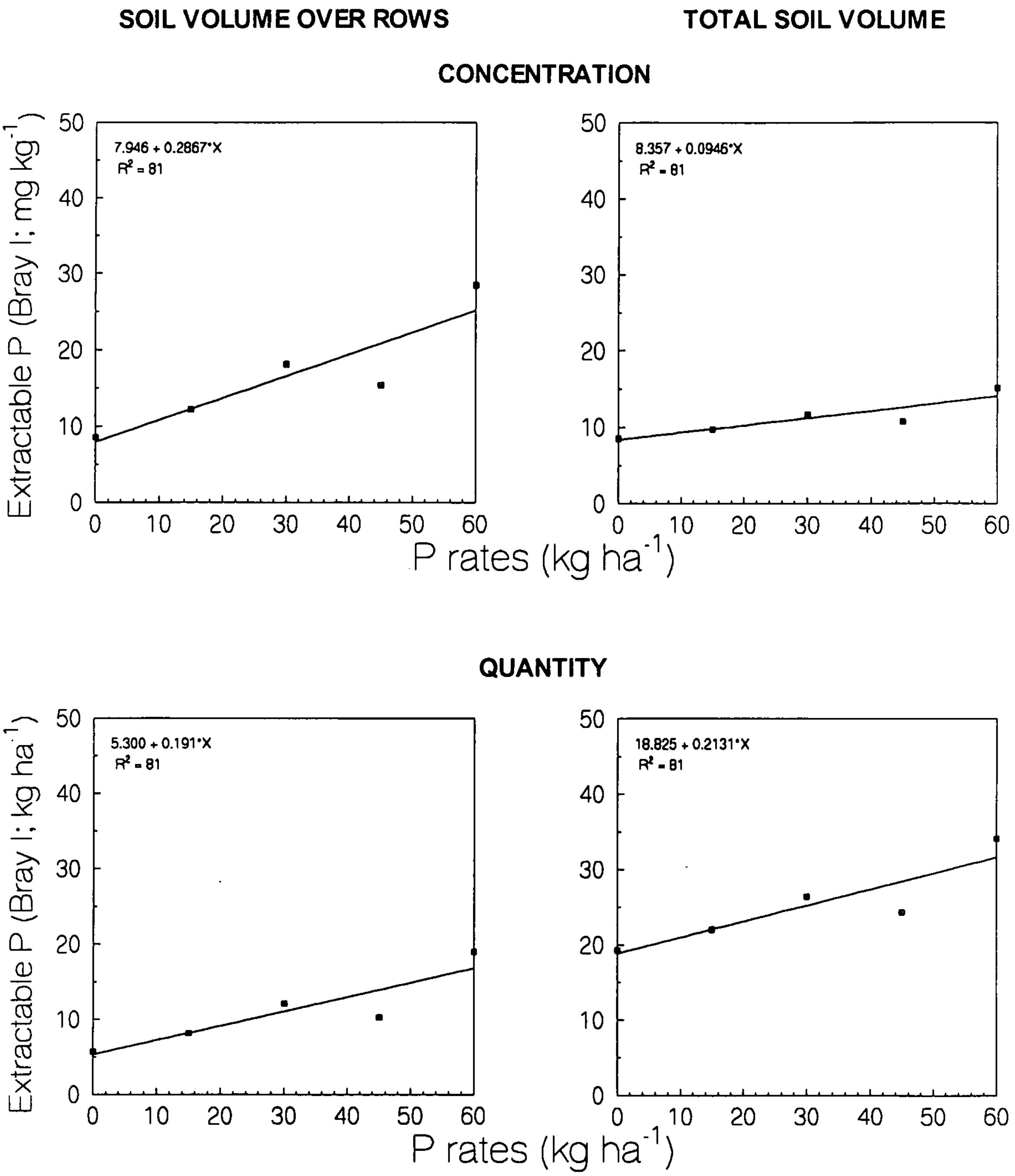


Figure 5.12 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Athole (P source trial; n = 5, consisting of 3 data points each).



SOIL VOLUME OVER ROWS

TOTAL SOIL VOLUME

CONCENTRATION

QUANTITY

Figure 5.13 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Belfast (P source trial; n = 5, consisting of 3 data points each).

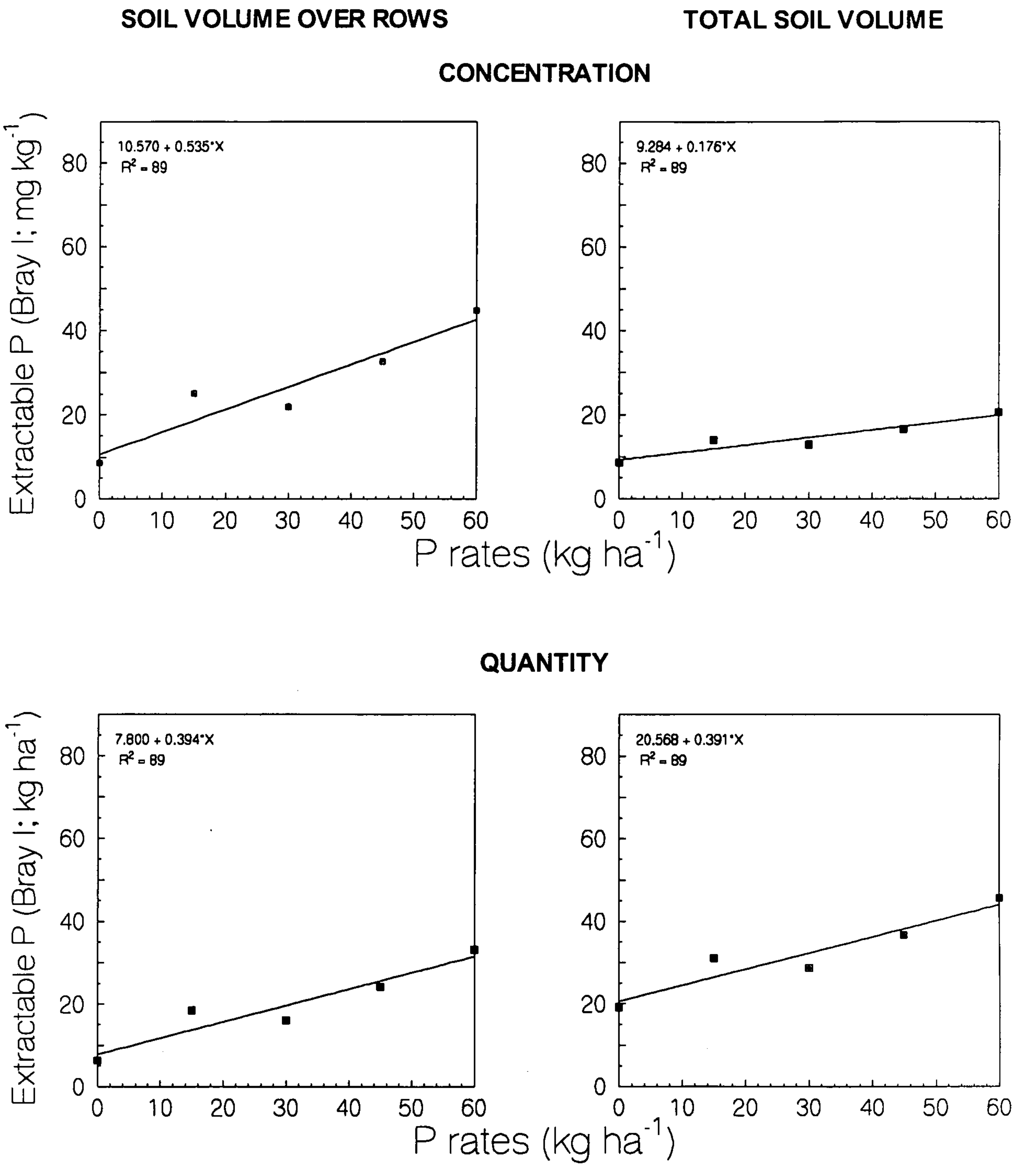


Figure 5.14 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Vrede (P source trial; n = 5, consisting of 3 data points each).

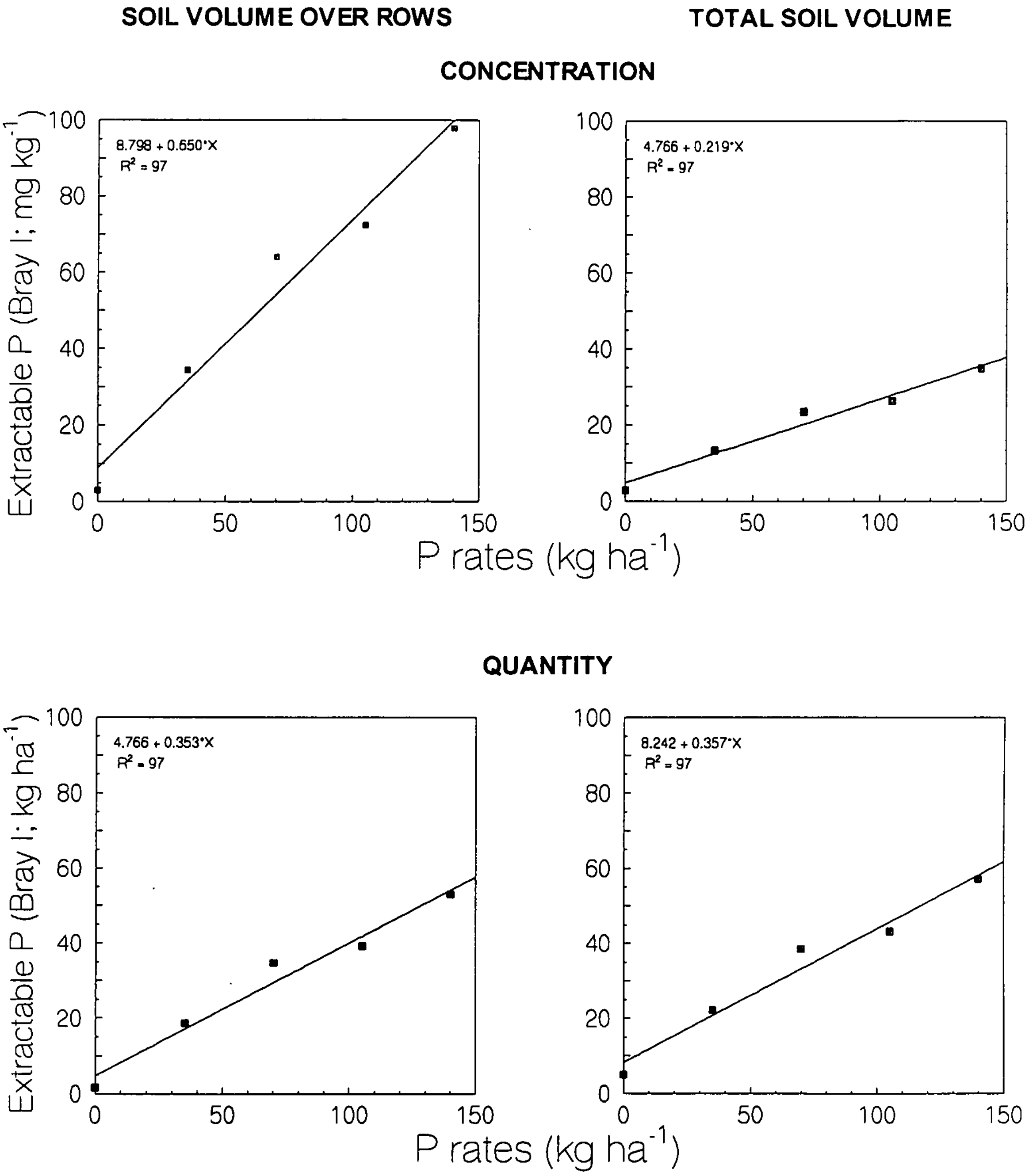
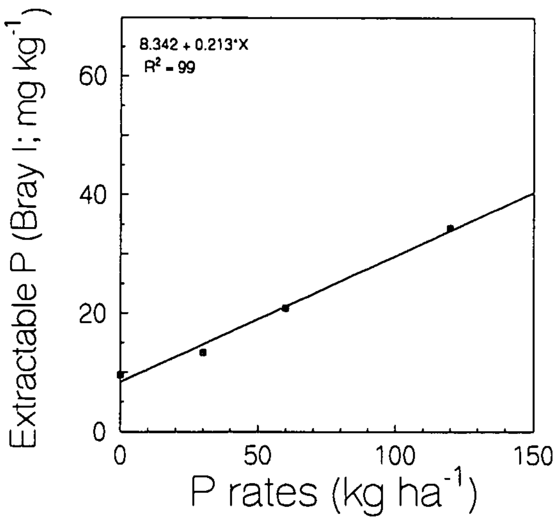


Figure 5.15 : Effects of P rates on extractable P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and for total soil volumes to a depth of 150 mm at Koppies (0.90 m trial; n = 5, consisting of 10 data points each).

TOTAL SOIL VOLUME

CONCENTRATION



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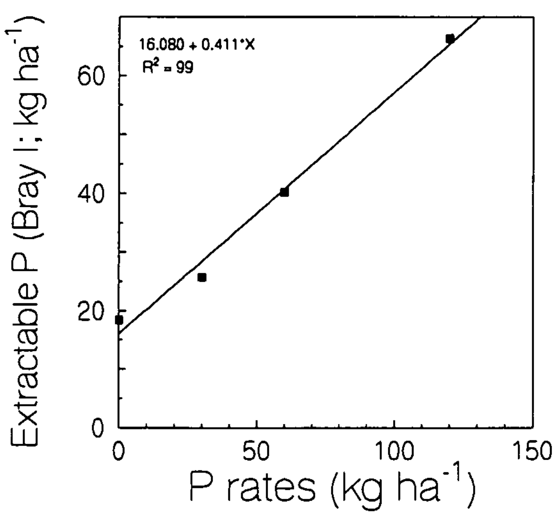

Figure 5.16 : Effects of P rates on extractable P (Bray 1) concentrations and quantities for total soil volumes to a depth of 150 mm at Dirkiesdorp (n = 4, consisting of 16 data points each).

Table 5.2 : Effects of P applications on extractable P (Bray 1) at Lichtenburg and P (Ambic 1) at all other localities for different soil volumes to a depth of 150 mm, presented as relationships

Locality	**Relationship [*Extractable P = a + b.Prates (kg ha^{-1})*]***			
	300 mm wide strip over rows	**R^2-value (%)**	**Total soil volume**	**R^2-value (%)**
		mg kg^{-1}		
Lichtenburg*	$Y = 0.9282 + 0.03933X$	85	$Y = 0.9230 + 0.01583X$	94
Wolmaransstad	$Y = 12.8525 + 0.38219X$	77	$Y = 11.2721 + 0.11146X$	93
Koppies (2.24 m)	$Y = -11.8860 + 0.93346X$	75	$Y = -0.8480 + 0.12351X$	75
Ventersdorp	$Y = -0.6180 + 1.10293X$	95	$Y = 1.3220 + 0.15100X$	95
Viljoenskroon	$Y = 9.3922 + 1.55634X$	96	$Y = 11.7469 + 0.52723X$	79
Stilfontein (N x P)	$Y = 6.5229 + 0.94249X$	98	$Y = 5.6610 + 0.19863X$	96
Stilfontein (P)	$Y = 5.9571 + 1.31143X$	91	$Y = 6.2314 + 0.26229X$	91
Heidelberg (N x P)	$Y = 0.5733 + 1.13894X$	92	$Y = 7.1358 + 0.28007X$	91
Heidelberg (Lime x P)	$Y = 9.3800 + 3.17543X$	98	$Y = 14.1960 + 0.63509X$	98
Athole	$Y = -0.3600 + 0.91933X$	91	$Y = 1.2882 + 0.30338X$	91
Belfast	$Y = 5.1700 + 0.17800X$	86	$Y = 5.6859 + 0.05874X$	86
Vrede	$Y = 10.3560 + 1.47520X$	99	$Y = 7.7457 + 0.48682X$	99
Kopies (0.90 m)	$Y = 3.1500 + 0.33683X$	97	$Y = 1.0620 + 0.11366X$	97
Dirkiesdorp	-	-	$Y = 5.0260 + 0.13912X$	99
		kg ha^{-1}		
Lichtenburg*	$Y = 0.2474 + 0.01061X$	83	$Y = 2.1437 + 0.03662X$	93
Wolmaransstad	$Y = 3.8186 + 0.11369X$	77	$Y = 24.9968 + 0.24711X$	93
Koppies (2.24 m)	$Y = -2.5920 + 0.20329X$	75	$Y = -1.3820 + 0.20086X$	75
Ventersdorp	$Y = -0.1880 + 0.33147X$	95	$Y = 3.0220 + 0.34547X$	95
Viljoenskroon	$Y = 4.1566 + 0.68823X$	96	$Y = 25.0596 + 1.14501X$	79
Stilfontein (N x P)	$Y = 3.3029 + 0.47729X$	98	$Y = 14.3281 + 0.50314X$	96
Stilfontein (P)	$Y = 3.0214 + 0.66429X$	91	$Y = 15.7780 + 0.66411X$	91
Heidelberg (N x P)	$Y = 0.29928 + 0.59695X$	92	$Y = 18.7851 + 0.73452X$	91
Heidelberg (Lime x P)	$Y = 3.7454 + 1.26795X$	98	$Y = 28.8704 + 1.29157X$	98
Athole	$Y = -0.2440 + 0.55987X$	91	$Y = 2.4902 + 0.58645X$	91
Belfast	$Y = 3.4540 + 0.11867X$	86	$Y = 12.8078 + 0.13232X$	86
Vrede	$Y = 7.6620 + 1.08907X$	99	$Y = 17.1606 + 1.07854X$	99
Kopies (0.90 m)	$Y = 1.7060 + 0.18257X$	97	$Y = 1.7280 + 0.18480X$	97
Dirkiesdorp	-	-	$Y = 9.6876 + 0.26816X$	99

Table 5.3 : Summary of the PRF's for all localities that were calculated from the slopes of previously established linear regression equations for different soil volumes

Locality	PRF's (kg P ha^{-1} required to raise soil test by one unit)							
	Soil volume over rows				Total soil volume			
	Ambic 1		Bray 1		Ambic 1		Bray 1	
	C	Q	C	Q	C	Q	C	Q
Lichtenburg	9.7	35.7	25.4	94.3	23.8	10.6	63.2	27.3
Wolmaransstad	2.6	8.8	1.9	6.3	9.0	4.0	6.4	2.9
Koppies (2.24 m)	1.1	4.6	0.6	2.8	8.1	5.0	4.7	2.9
Ventersdorp	0.9	3.0	0.8	2.7	6.6	2.9	6.3	2.7
Viljoenskroon	0.6	1.5	0.7	1.7	1.9	0.9	2.2	1.0
Stilfontein (N x P)	1.1	2.1	0.8	1.6	5.0	2.0	3.5	1.4
Stilfontein (P)	0.8	1.5	0.7	1.5	3.8	1.5	3.7	1.5
Heidelberg (N x P)	0.9	1.7	1.0	1.8	3.6	1.4	3.9	1.5
Heidelberg (Lime x P)	0.3	0.8	0.3	0.8	1.6	0.8	1.7	0.8
Athole	1.1	1.8	1.6	2.6	3.3	1.7	4.8	2.5
Belfast	5.6	8.4	3.5	5.2	17.0	7.6	10.6	4.7
Vrede	0.7	0.9	1.9	2.5	2.1	0.9	5.7	2.6
Kopies (0.90 m)	3.0	5.5	1.5	2.8	8.8	5.4	4.6	2.8
Dirkiesdorp	-	-	-	-	7.2	3.7	4.7	2.4

C = Concentration (mg kg^{-1}) and Q = quantity (kg ha^{-1})

5.3.3 Soil phosphorus requirements in relation to properties

The PRF's given in Table 5.3 were related to different soil properties by means of simple and multiple regressions. Unfortunately, the PRF's established for concentration in the soil volume over the rows could not be used in this exercise. This resulted from the different row widths at the various localities, i.e. an application rate of 80 kg P ha^{-1} resulted in applications of 1.79, 1.20 and 0.72 kg P row^{-1} of 100 m length at 2.24, 1.50 and 0.90 m row widths, respectively. Hence the same P application rate will therefore result in different extractable P concentrations at different row widths. The soil properties used in these regression analyses are those recorded in the topsoil during characterization of the studied soils as described in Section 3.3.

Table 5.4 : Explanation of variation (R^2), correlation coefficients (r) and probabilities (*P*) for the simple regression analyses between PRF's and soil properties

Soil properties	**Ambic 1**									**Bray 1**								
	Volume over rows			**Total soil volume**						**Volume over rows**			**Total soil volume**					
	Q			**C**			**Q**			**Q**			**C**			**Q**		
	R^2 (%)	**r**	***P***	**R^2 (%)**	**r**	***P***	**R^2 (%)**	**r**	***P***	**R^2 (%)**	**r**	***P***	**R^2 (%)**	**r**	***P***	**R^2 (%)**	**r**	***P***
Clay (%)	8	-0.29	ns	12	-0.35	ns	18	-0.42	ns	2	-0.15	ns	5	0.21	ns	9	0.30	ns
Silt (%)	24	0.50	ns	19	0.44	ns	12	-0.35	ns	24	0.49	ns	21	0.46	ns	16	0.39	ns
Silt + Clay (%)	23	-0.48	ns	40	0.63	0.0150	43	0.66	0.0110	11	0.33	ns	24	0.49	ns	31	0.56	0.0390
Exchangeable Ca (mg kg^{-1})	41	0.64	0.0190	43	0.66	0.0110	56	0.75	0.0020	30	0.55	0.0540	29	0.54	0.0460	39	0.63	0.0170
Exchangeable Mg (mg kg^{-1})	9	-0.30	ns	8	-0.29	ns	13	0.37	ns	14	0.38	ns	13	0.36	ns	11	0.33	ns
Exchangeable Fe (mg kg^{-1})	40	0.63	0.0206	30	0.55	0.0420	40	0.63	0.0160	26	0.51	ns	24	0.49	ns	27	0.52	0.0560
Exchangeable Mn (mg kg^{-1})	41	0.64	0.0100	30	0.58	0.0410	46	0.68	0.0080	31	0.56	0.0480	24	0.49	ns	34	0.58	0.0280
Exchangeable Zn (mg kg^{-1})	11	-0.33	ns	9	-0.30	ns	17	0.41	ns	5	-0.23	ns	3	-0.18	ns	6	-0.25	ns
Organic C (%)	2	0.16	ns	8	0.27	ns	7	0.27	ns	7	-0.27	ns	13	0.36	ns	18	-0.43	ns
Exchangeable acidity (cmol$_c$kg^{-1})	15	-0.39	ns	14	0.38	ns	17	0.42	ns	2	-0.13	ns	2	-0.13	ns	2	-0.15	ns
pH(KCl)	50	0.71	0.0070	58	0.76	0.0020	70	0.83	0.0000	35	0.59	0.0330	35	0.59	0.0250	42	0.65	0.0120
pH(H_2O)	50	0.71	0.0070	51	0.71	0.0040	64	0.80	0.0000	32	0.57	0.0440	29	0.54	0.0480	38	0.62	0.0180
CEC (cmol$_c$kg^{-1})	33	0.58	0.0410	35	0.59	0.0260	48	0.69	0.0060	22	0.47	ns	22	0.47	ns	32	0.57	0.0340
Degree of leaching (clay)[1]	70	0.83	0.0040	71	0.85	0.0010	78	0.88	0.0000	60	0.78	0.0020	60	0.78	0.0010	66	0.81	0.0010
Degree of leaching (silt + clay)[2]	45	0.67	0.0120	47	0.68	0.0070	60	0.77	0.0010	37	0.61	0.0280	37	0.61	0.0210	45	0.67	0.0090

C = Concentration (mg kg^{-1}) and Q = Quantity (kg ha^{-1}); [1] Degree of leaching (DL_c) = [((Ca/200 + K/391 + Mg/122 + Na/230; cmol$_c$ kg soil^{-1})*100)/Clay (%)]; [2] Degree of leaching = [((Ca/200 + K/391 + Mg/122 + Na/230; cmol$_c$ kg soil^{-1})*100)/Silt + clay (%)]

The explanation of variation, correlation coefficients and probabilities for the simple regression analyses between PRF's and soil properties are summarized in Table 5.4. The soil properties which explained most of the variation in PRF's, are the degree of leaching based on the clay content (DL_c), followed by pH(KCl and H_2O), then by the degree of leaching based on the silt-plus-clay content and then the exchangeable Ca content. Some of the other soil properties also explained the variation in PRF's significantly, but inconsistently. Overall the R^2-values were low (between 2 and 64 %) and therefore none of the simple regression equations can be used with confidence to predict the PRF's of soils, except the DL_c (summarized in Table 5.5) with R^2-values ranging between 60 and 78 % which appeared to be promising and warrants further investigation.

Table 5.5 : Simple regression equations for the determination of Ambic 1 and Bray 1 PRF's

Soil volumes	Equations[1]	R^2-values (%)
Over rows	Quantities (kg ha^{-1})	
	PRF (Ambic 1) = $(0.713 + 0.0489DL_c)^2$	70
	PRF (Bray 1) = $\exp(0.096 + 0.0384DL_c)$	60
Total		
	PRF (Ambic 1) = $0.573 + 0.1114DL_c$	78
	PRF (Bray 1) = $(0.772 + 0.0374DL_c)^2$	66
	Concentrations (mg kg^{-1})	
	PRF (Ambic 1) = $1.280 + 0.2314DL_c$	71
	PRF (Bray 1) = $(1.136 + 0.0551DL_c)^2$	60

[1] - DL_c as explained in Table 5.4

Multiple regressions were consequently done between the PRF's and soil properties for Ambic 1 (Table 5.6) and Bray 1 (Table 5.7). R^2-values obtained by multiple regressions in decreasing order ranged between 83 and 99 % for exchangeable Ca, Mg and silt content, between 70 and 98 % for exchangeable Ca and Mg, between 77 and 88 % for exchangeable Ca, K and silt content, between 62 and 85 % for silt content and DL_c, between 68 and 78 % for exchangeable Ca, K and between 47 and 79 % for exchangeable Ca and silt content. Any of the first five regressions could be used for the estimation of PRF's. This aspect warrants further research.

Table 5.6 : Summary of multiple regression analyses between PRF's (Ambic 1) and soil properties

		Equations[1]	R^2-values	*P*-values					
					---------------- Parameters ----------------				
			(%)	Model	Ca	Mg	K	Silt	$\mathrm{DL_c}$
Soil volumes over rows		**Quantities (kg ha^{-1})**							
PRF (Ambic 1)	=	3.106 + 0.0089Ca - 0.0410Mg	93	0.0000	0.0000	0.0000	-	-	-
	=	7.409 + 0.0068Ca - 0.0799K	78	0.0006	0.0002	-	0.0013	-	-
	=	-7.164 + 0.0044Ca + 0.9692Silt	66	0.0044	0.0036	-	-	0.0112	-
	=	0.715 + 0.0065Ca + 0.5974Silt - 0.0618K	88	0.0002	0.0001	-	0.0033	0.0235	-
	=	-1.358 + 0.0084Ca + 0.4686Silt - 0.0343Mg	99	0.0000	0.0000	0.0000	-	0.0000	-
	=	-7.698 + 0.6281Silt + 0.3175$\mathrm{DL_c}$	80	0.0003	-	-	-	0.0219	0.0002
Total soil volumes									
PRF (Ambic 1)	=	2.010 + 0.0024Ca - 0.0076Mg	72	0.0008	0.0003	0.0171	-	-	-
	=	2.956 + 0.0022Ca - 0.0178K	75	0.0005	0.0001	-	0.0087	-	-
	=	-0.568 + 0.0016Ca + 0.2664Silt	77	0.0003	0.0001	-	-	0.0058	-
	=	0.883 + 0.0021Ca + 0.1983Silt - 0.0127K	87	0.0001	0.0000	-	0.0196	0.0134	-
	=	0.175 + 0.0022Ca + 0.1997Silt - 0.0048Mg	83	0.0003	0.0002	0.0762	-	0.0269	-
	=	-0.415 + 0.1356Silt + 0.1090$\mathrm{DL_c}$	84	0.0000	-	-	-	0.0546	0.0000
		Concentrations (mg kg^{-1})							
PRF (Ambic 1)	=	4.896 + 0.0053Ca - 0.0211Mg	70	0.0014	0.0004	0.0054	-	-	-
	=	7.251 + 0.0045Ca - 0.0456K	68	0.0017	0.0005	-	0.0068	-	-
	=	-1.656 + 0.0031Ca + 0.6698Silt	70	0.0014	0.0012	-	-	0.0054	-
	=	2.084 + 0.0043Ca + 0.4942Silt - 0.0329K	84	0.0003	0.0001	-	0.0141	0.0113	-
	=	0.613 + 0.0049Ca + 0.4662Silt - 0.0147Mg	83	0.0004	0.0002	0.0217	-	0.0216	-
	=	-1.746 + 0.4154Silt + 0.2239$\mathrm{DL_c}$	85	0.0000	-	-	-	0.0105	0.0000

[1] - Exchangeable cations used in equations in mg kg^{-1}, silt content in % and $\mathrm{DL_c}$ as explained in Table 5.4

Table 5.7 : Summary of multiple regression analyses between PRF's (Bray 1) and soil properties

		Equations[1]	**R^2-values**	***P*-values**					
					Parameters				
			(%)	**Model**	**Ca**	**Mg**	**K**	**Silt**	**DL_c**
Soil volumes over rows		**Quantities (kg ha^{-1})**							
PRF (Bray 1)	=	3.858 + 0.0246Ca - 0.1222Mg	98	0.0000	0.0000	0.0000	-	-	-
	=	15.665 + 0.177Ca - 0.224K	74	0.0012	0.0004	-	0.0017	-	-
	=	-19.510 + 0.0104Ca + 2.0822Silt	47	0.0405	0.0240	-	-	0.0778	-
	=	5.619 + 0.0174Ca + 0.8966Silt - 0.1971K	77	0.0032	0.0007	-	0.0079	0.3012	-
	=	0.254 + 0.0242Ca + 0.3783Silt - 0.1168Mg	99	0.0000	0.0000	0.0000	-	0.0666	-
	=	-21.593 + 1.2629Silt +0.7883DL_c	62	0.0075	-	-	-	0.1784	0.0039
Total soil volumes									
PRF (Bray 1)	=	2.094 + 0.0068Ca - 0.0324Mg	97	0.0000	0.0000	0.0000	-	-	-
	=	4.918 + 0.0050Ca - 0.0581K	75	0.0005	0.0001	-	0.0010	-	-
	=	-4.062 + 0.0030Ca + 0.5813Silt	52	0.0171	0.0101	-	-	0.0492	-
	=	1.640 + 0.0049Ca + 0.3136Silt - 0.0501K	81	0.0007	0.0001	-	0.0035	0.1296	-
	=	0.590 + 0.0066Ca + 0.1637Silt - 0.0301Mg	99	0.0000	0.0000	0.0000	-	0.0120	-
	=	-4.301 + 0.3323Silt + 0.2239DL_c	68	0.0020	-	-	-	0.1453	0.0011
		Concentrations (mg kg^{-1})							
PRF (Bray 1)	=	4.896 + 0.0158Ca - 0.0774Mg	97	0.0000	0.0000	0.0000	-	-	-
	=	11.535 + 0.0113Ca - 0.1373K	73	0.0008	0.0003	-	0.0013	-	-
	=	-9.750 + 0.0067Ca + 1.3814Silt	79	0.0233	0.0153	-	-	0.0508	-
	=	3.692 + 0.0111Ca + 0.7501Silt - 0.1181K	78	0.0012	0.0002	-	0.0044	0.1382	-
	=	1.402 + 0.0154Ca + 0.3801Silt - 0.0722Mg	98	0.0000	0.0000	0.0000	-	0.0134	-
	=	-10.552 + 0.8255Silt + 0.5081DL_c	66	0.0027	-	-	-	0.1319	0.0016

[1] - Exchangeable cations used in equations in mg kg^{-1}, silt content in % and DL_c as explained in Table 5.4

The DL_c is made up by the sum of the basic cations in relation to the clay content, implicating a stable parameter in terms of variation in cations. Furthermore, all the variables included in the equation forms part of routine analyses in agricultural laboratories, making it easy to obtain. Therefore, since DL_c explained variation in simple regressions for both Ambic 1 and Bray 1 at acceptable levels (R^2-values between 60 and 78 %), it should be considered above the multiple regression equations as an obvious parameter for the determining of PRF's.

5.4 Conclusion

The objective of this study to relate extractable P concentrations and quantities as determined by either the Ambic 1 or Bray 1 extractants in soil volumes over rows and total soil volumes to P rates, was largely met. There were large differences between PRF's for different soils, indicating that the soils differed in their response to applied P which is an aspect that should be implemented in fertilizer recommendations. An attempt to relate the PRF's to soil properties by means of simple and multiple regression was successful. Degree of leaching based on the clay content in simple regressions should be considered as an obvious parameter for the determination of PRF's. Validation of these equations should be done over many soils.

However, obtained results can already be implemented in phosphorus recommendation on different soils. Phosphorus requirement factors reported in this study are not related to those in previous reports (LNR-Instituut vir Graangewasse, 1994) and differ largely with respect to the range of P requirements. A task team assisting the ARC-Grain Crops Institute decided on PRF's of 5, 7 and 9 kg P ha^{-1} for soils with clay contents of <10 %, 10 - 20 % and 21 - 35 %, respectively (LNR-Instituut vir Graangewasse, 1994). No PRF's were chosen for soils with clay content higher than 35 %. In this study it was shown that PRF's could not be related to clay content only, but also to other soil properties as already explained (Tables 5.4 to 5.7), for instance exchangeable Ca, K, Mg, silt content and degree of leaching based on clay content. The general impact of the implementation of the acquired PRF's compared to those currently in use is very difficult to assess, but certainly the effectiveness of supplementing P shortages should greatly be improved.

CHAPTER 6

RELATIONSHIPS BETWEEN EXTRACTABLE SOIL PHOSPHORUS AND MAIZE YIELD

6.1 Introduction

Substantial increases in productivity per hectare will in future be essential to meet the needs of a rapidly increasing world population since the total land area used for food and fibre production is not likely to increase. A study by the Food and Agriculture Organization of the United Nations of 41 countries found a positive relation between the amount of fertilizer used and the yield of crops produced per hectare. Thus throughout the world it is seen that the use of fertilizers to improve soil fertility play an important role in food production and is related to the overall economic activity in a country (IFA, s.a.; Foth & Ellis, 1997). In the United States of America development and increased use of fertilizer is directly related to increased crop productivity (Havlin et al., 1999).

However, soils differ widely in their ability to meet plant requirements for nutrients, as most have only a moderate natural soil fertility that can be considerably improved by soil amendments (IFA, s.a.). Application of too little plant nutrients will result in deficiencies probably accompanied with visual deficiency symptoms, while plants that are moderately deficient usually exhibit no visual symptoms, although yield potential is reduced. Added nutrients will maximize yield potential and increase nutrient concentration in the plant. Thus, optimum productivity of any cropping system depends on an adequate supply of plant nutrients (Havlin et al., 1999).

Fertilizer recommendations can only be justified if they result in an increase in profit above costs (Colwell, 1994). The extent to which the use of fertilizers contributes to this objective depends not only upon the kinds, amounts and ways of fertilizer application and the resulting crop responses, but also upon the costs of fertilization and the prices received for the crops. Both the physical and economic realities must be recognized (Black, 1993). This is confirmed by Mengel & Rehm (2000), but they added that the efficiency of nutrient application is one of the major keys which determines the overall effectiveness of a fertilizer program. Westerman, Ruan & Johnson (2000) pointed out that nutrient use efficiencies seldom exceed 50 % in most grain production systems.

According to Simpson (1991) whatever the model of yield curve with increasing fertilizer rate for a given crop, the resources and energy spent on squeezing the last few kilograms of yield per hectare are being used very inefficiently and uneconomically. From both the short-term profit motive and the long-term conservation motive, maximum yield production is inefficient. The aim should therefore rather be maximum economic yield which is usually lower than maximum yield. Maximum economic yield is defined as the point at which the last increment of fertilizer input pays for itself and this varies among soils, although on most farms it is much higher than those generally achieved, regardless of the soil (Havlin et al., 1999). Thus the optimal rate of application of fertilizer to a crop should be that rate which produces maximum economic return. However, Black (1993) points out that the economics of fertilization are very complex, as the optimum economic applications of fertilizers could be defined to suit the case of the agronomist, the economist, a tenant, a landlord or the consumer.

The still widely used practice of deciding rates of fertilizer use on the basis of local experience or general data for crop requirements is certainly useful for obtaining at least medium yield levels, but neither very effective nor economic (IFA, s.a.). Therefore knowledge of the relationship between soil test results and crop response is essential for providing the most appropriate nutrient recommendation (Havlin et al., 1999). Thus, it remains necessary to assess empirically the nutrient status of soils and plants in order to provide guidelines for effective fertilizer use (IFA, s.a.). The relationship between yield, nutrient level in soil and deficiency in plants can be illustrated by means of a response curve (Black, 1993) and is shown in Figure 6.1.

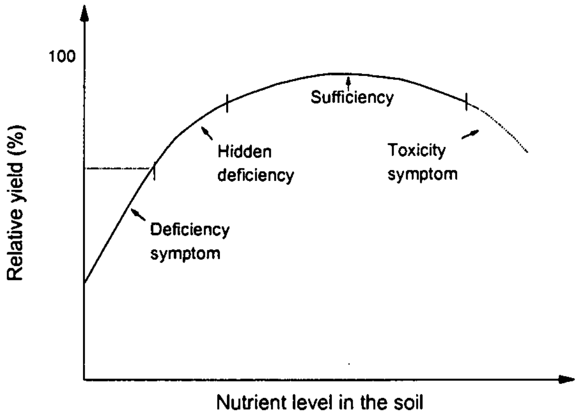

Figure 6.1 : Relationship between relative yield, nutrient level in soil and deficiencies in plants (from Jones, 1982).

The Fertilizer Society of South Africa (MVSA, 1997) uses soil P status as well as target yield as the basis for fertilizer recommendations while researchers have indicated that the relation between soil P status and relative yield together with soil responses should be the only basis (Farina et al., 1993). Mallarino & Blackmer (1992) used relative yields as an expression of yield response in models relating crop response with soil test values in order to identify critical P concentrations. Although the concept of percentage sufficiency level is often associated with the use of relative yield in soil testing, the analyses showed that arbitrary selection of percentage sufficiency levels is a questionable practice. Because direct economic analyses cannot be applied to relative yields, the problem of selecting an optimal sufficiency level in advance has no straightforward solution even if crop and fertilizer prices are considered. In their study the 95 % sufficiency level resulted in the highest returns for both the quadratic-plateau and exponential models. Cox (1992) used data from a long term experiment to determine the range in critical soil P levels using the linear-plateau and exponential functions. Relationships between yield as well as relative yield with Mehlich 3 extractable P were determined. Timing of sampling as well as information on fertilizer applications were not reported. At 95 % of the maximum yield the critical P level determined by the linear-plateau function (18 - 33 mg l^{-1} with an average of 26) differed very much from that determined by the exponential model (23 - 54 mg l^{-1} with an average of 39). When economic considerations were applied to the exponential function, the results indicated that 95 % maximum yield was a reasonable estimate for maize. Other researchers suggesting the use of relative yield and soil test values are Sims (2000) and Havlin et al. (1999).

Various South African researchers also compared fertilizer P application rates or soil P test values with yield or relative yield to determine economic optima for maize. For example, Möhr (1972) investigated P norms for maize using data from 86 NPK field trials conducted by the Fertilizer Society of South Africa or its members on different soil types scattered over the maize triangle. A significant correlation between soil P content and maize response was found where the experimental data was grouped on the basis of soil form. Later Möhr (1975a) reported on optimum soil P levels for series of the Avalon and Hutton soil forms. During this study data from 41 depletion experiments on maize were used and it was concluded that optimum soil P, in terms of maize yield response, is mainly determined by soil form and degree of leaching. For poorly leached Avalon soils, the optimum level is approximate 25 mg kg^{-1} and for highly leached Avalons soils approximately 30 mg kg^{-1} with Bray 2 extractions. Farina & Mapham (1973) used data obtained from a long term maize fertilization trial conducted on a sandy loam soil in KwaZulu-Natal and related 0.05 N H_2SO_4 extractable P concentrations to relative yields. P levels of 14 and 18 mg l^{-1} were needed in this particular soil to obtain 90 and 95 % relative yields, respectively. In another exercise Farina, Mapham & Channon (1975) compared maize yield responses to N and P fertilization in three soil-bioclimatic systems in KwaZulu-Natal, to illustrate the importance of economic considerations in the formulation of fertilizer recommendations. Nienaber & Groenewald (1979a and b) also used the concept of relative yield and Bray 2 soil test on Avalon and Hutton soils scattered in the maize triangle with different degrees of leaching to derive optimum soil P levels. On low, medium and highly leached Avalon soils it was found that P levels of respectively 12, 16 and 23 mg kg^{-1} for a 90 % relative yield and 19, 22 and 29 mg kg^{-1} for a 95 % relative yield were needed. However, on low and medium leached Hutton soils P levels of 23 and 30 mg kg^{-1} were needed to obtain 90 and 95 % relative yields, respectively. Using data from a long term field experiment in KwaZulu-Natal, Farina, Channon & Minnaar (1980) developed a predictive equation relating yields to N application rates and soil P test values. The data suggested N applied and extractable soil P to be closely related to yields in the individual seasons. In other studies Farina & Channon (1987) and Farina (1989) reported that relative yields of 90 and 95 % were obtained at Ambic 1 extractable P levels of 7 and 13 mg l^{-1} on a clay loam soil in KwaZulu-Natal, respectively. Bornman (1991a and b) also made use of the concept of relating relative yields to soil P test values to derive optimum economic P fertilizer recommendations for maize. The data from a field trial in the Wesselsbron area showed that a relative yield of 90 and 95 % was obtained at Bray 1 extractable P levels of 7 and 13 mg kg^{-1}, respectively. A study by Farina et al. (1993) indicated that optimum soil P test values to reach maximum yield increase with increasing sample density, implicating increasing sand and decreasing clay contents. A linear relationship was established for four soils ranging in sample density from approximately 1.0 to 1.6 g ml^{-1}, with corresponding clay contents of 55 to 5 % and optimum soil test values of 12 to 35 mg l^{-1} Ambic 1 P. In most of the above mentioned instances good relationships were established, however P fertilizer was broadcasted in the majority of these studies and therefore it cannot be compared with practices where P fertilizers are band placed.

In semi-arid South Africa where fertilizers are usually band placed at planting, yield should be related to soil P status by taking the effects of band placement into consideration. The relations of both inorganic soil N and extractable soil P to yield under such conditions were reported by Landman (1995), while Smalberger (2001) reported only on the contribution of inorganic N.

Landman (1995) established acceptable relationships (R^2-values ranging between 78 and 83 %) between Bray 1 extractable soil P and relative biomass at two localities, viz. Klerksdorp and Viljoenskroon. At

Klerksdorp 38.4 mg kg^{-1} or 17.7 kg ha^{-1} was needed in the soil volume over the rows to obtain relative biomass of 90 %, while 20.7 mg kg^{-1} or 51 kg ha^{-1} extractable P was needed in the total soil volume to obtain the same relative biomass. The equivalent values according to the Ambic 1 method were 32.0 mg kg^{-1} or 14.8 kg ha^{-1} extractable P over the rows and 14.4 mg kg^{-1} or 35.6 kg ha^{-1} extractable P in the total soil volume. At Viljoenskroon 43.9 mg kg^{-1} or 19.4 kg ha^{-1} extractable P in the soil volume over the rows and 30.0 mg kg^{-1} or 64.2 kg ha^{-1} extractable P in the total soil volume was required to obtain relative biomass of 90 %. The equivalent values according to the Ambic 1 method were 28.1 mg kg^{-1} or 12.4 kg ha^{-1} extractable P over the rows and 18.1 mg kg^{-1} or 38.7 kg ha^{-1} in the total soil volumes. Unfortunately, above mentioned values were established with biomass yield which is not always directly related to grain yield.

According to an investigation by Human & Van Biljon (1994) the major dryland maize producing area west of the Drakensberg in South Africa, an optimum Bray 1 P concentration of 17 ± 2 mg kg^{-1} at band placements of 5 to 11 kg P ha^{-1} was required for 95 % relative yield (Figure 2.13). Considering the high price of fertilizers, fluctuating maize prices and the unstable maize producing environment in South Africa due to lack of rain as well as large variation in seasonal rainfall distribution, it appears as if soil P should be managed to obtain 90 % rather than 95 % relative yield. The main objective of this study was to determine the extractable P concentrations and quantities based on both Ambic 1 and Bray 1 extractions that are required in soil volumes over rows as well as in total soil volumes to obtain either 90 or 95 % relative yield for different soils. In addition it was realised that these threshold values should be related to soil properties if they differ between soils.

6.2 Procedure

Some general information on the accumulation of grain yield data at the different trials is presented in Section 3.6.2. The effect of treatments on absolute grain yield over seasons where applicable, was determined for each trial by analyses of variance, where-after the mean absolute grain yield values for each season at the different trials were transposed to percentages of the maximum grain yield. The objective was to obtain absolute and relative mean grain yield values for each season which could be related to the extractable soil P values. However, details on statistics of treatment effects on grain yield are summarized in Table 6.1.

Only some of the data were suitable for the establishment of relationships between grain yield and extractable soil P as indicated in Table 6.2, i.e. Lichtenburg, Wolmaransstad, Koppies (both trials), Ventersdorp, Viljoenskroon, Stilfontein (N x P), Heidelberg (N x P) and Heidelberg (Lime x P) localities for soil volumes over rows, and all localities except Heidelberg (Lime x P) for the total soil volumes.

Relationships between grain yield and extractable soil P were established with Bray 1 values for all trials, except at Lichtenburg where Ambic 1 was used. Simple regression analysis was done for both absolute and relative grain yield. The threshold extractable concentrations or quantities needed in the 0-150 mm soil layer at the time of planting until four to six weeks after planting, to obtain either 90 or 95 % relative grain yield, were derived from these simple regressions. After obtaining the threshold extractable values for each trial, the equivalent opposite value in either Ambic 1 or Bray 1 was calculated using the equations reported in Table 4.4. Threshold P values for both Ambic 1 and Bray 1 were then subjected to simple and multiple regression analyses with soil properties.

6.3 Results and discussion

6.3.1 Relationships over soils

Effects of extractable soil P (Bray 1) concentrations (mg kg^{-1}) and quantities (kg ha^{-1}) in soil volumes over rows and in total soil volumes on absolute and relative yield are presented as relationships in Figures 6.2 and 6.3, respectively. For this exercise the Ambic 1 values for the Lichtenburg locality were converted to equivalent Bray 1 values by using the relevant equations in Table 4.4.

Significant relationships could not be established for absolute yields (Figure 6.2), but in contrast the relationships for relative yields (Figure 6.3) were significant. This illustrates that the use of relative rather than absolute yields results in more significant relationships which explains more variation from which threshold extractable P values can be derived. However, relationships established for relative yield over soils showed R^2-values of less than 38 %, implying that threshold extractable P values obtained from these relationships will not necessarily be applicable to any particular soil. Consequently, these relationships were established for each and every soil.

6.3.2 Relationships for individual soils

Effects of extractable P concentrations (mg kg^{-1}) and quantities (kg ha^{-1}) in soil volumes over rows and in total soil volumes on absolute and relative yield are presented as relationships for each locality in Figures 6.4 to 6.21. Relationships for all localities (Figures 6.6 to 6.21) were done according to the Bray 1 extractant, except those for Lichtenburg (Figures 6.4 and 6.5) which were according to Ambic 1 values for the same reason as explained in Section 5.3.2. Derived threshold extractable soil P values according to Bray 1 were then transposed to that of Ambic 1 and *vice versa.* Relationships established for Heidelberg (Lime x P) and Dirkiesdorp were only for the total soil volumes.

Generally, extractable soil P explained the variation in relative yields better than the variation in absolute yields (Figures 6.4 to 6.21). Relationships for absolute yield illustrate the point raised by Farina et al. (1993) that the P requirement of maize is not directly related to absolute yield. However, most researchers assume that the P requirement of crops like that of N requirement, is directly related to absolute yield potential. In other words when the yield potential is lower the P requirement will be lower and *vice versa.* Research results obtained in KwaZulu-Natal by Farina et al. (1993) showed that it is inappropriate to adjust the P requirement of maize according to the absolute yield. Recommendations on P fertilization should therefore according to them only be based on optimum soil P values and relative yields, irrespective of yield potential.

The R^2-values for relationships between relative yield and extractable P concentrations and quantities for soil volumes over rows were in increasing order 33, 42, 46, 51, 76, 83, 83, 95 and 97 % for the Heidelberg (Lime x P), Wolmaransstad, Viljoenskroon, Lichtenburg, Heidelberg (N x P), Koppies (both trials), Stilfontein (N x P) and Ventersdorp trials, respectively (Figures 6.4 to 6.21). In comparison the R^2-values for relationships between relative yield and extractable P concentrations and quantities for total soil volumes in increasing order were 38, 46, 48, 82, 83, 83, 83, 90 and 98 % for the Wolmaransstad, Lichtenburg, Viljoenskroon, Dirkiesdorp, Koppies (both trials), Heidelberg (N x P), Ventersdorp and Stilfontein trials, respectively. Thus, R^2-values obtained for relationships between relative yield and extractable P concentrations and quantities in soil volumes over rows at Heidelberg (N x P), Koppies (both trials), Stilfontein and Ventersdorp ranged between 76 and 97 %, while that for total soil volumes ranged between 83 and 98 %. A R^2-value of 82 % was also obtained for total soil volumes at Dirkiesdorp. The R^2-values for these relationships for soil volumes over rows at Heidelberg (Lime x P), Wolmaransstad, Viljoenskroon and Lichtenburg varied between 33 and 51 %, while that for total soil volumes varied between 38 and 48 %.

Table 6.1 : Statistics on treatment effects for different trials

		P-values for Yield [4]												
Trial	**Locality**	**Plants as covariance**	**Application rates**			**Season**	**P source**	**Lime**	**Season x N**	**Season x P**	**N x P**	**Season x N x P**	**LSD[1] (kg ha^{-1})**	**CV[2] (%)**
			N	**P**	**K**									
1	Lichtenburg	-	<0.001	<0.001	-	-	-	-	ns	<0.001	<0.001	ns	348	11
2	Wolmaransstad	-	<0.001	<0.001	-	-	-	-	<0.001	<0.001	<0.001	ns	531	22
3	Koppies (2.24 m)	<0.001	ns	<0.001	-	<0.001	-	-	0.0080	0.0010	ns	ns	591	44
4	Ventersdorp	-	ns	<0.001	-	-	-	-	-	-	ns	-	328	11
5	Viljoenskroon	-	<0.001	<0.001	-	-		-	<0.001	ns	<0.001	ns	1575	25
6	Stilfontein (N x P)	-	ns	0.0260	-	<0.001	-	-	ns	ns	ns	ns	799	42
7	Stilfontein (P)	-	-	0.0030	-	-	0.0080	-	-	0.0010	-	-	1016	26
8	Heidelberg (N x P)	-	<0.001	<0.001	-	-	-	-	<0.001	<0.001	<0.001	ns	1103	21
9	Heidelberg (Lime x P)	-	-	<0.001	-	-	-	0.0070	-	<0.001	-	-	879	16
10	Athole	-	-	-	-	-	-	-	-	-	-	-	-	-
11	Belfast	-	-	ns	-	-		-	-	-	-	-	791	-
12	Vrede	-	-	-	-	-	-	-	-	-	-	-	-	-
13	Koppies (0.90 m)	-	ns	0.0010	-	<0.001	-	-	ns	0.0420	ns	ns	384	39
14	Dirkiesdorp	-	<0.001	<0.001	0.0060	-	-	-	<0.001	0.0290	ns	0.0280	-[3]	14

[1] - Least significant difference; [2] - Coefficient of variance; [3] - Cannot be calculated because of no reps; [4] - = not applicable

Table 6.2 : Some relevant information on the accumulation of yield data that was used for the determination of relationships between grain yield and extractable P

Localities	**Remarks**
Lichtenburg	Data from all seasons were used for the establishment of relationships, except that of the third season, i.e. 1991/92, which was very dry (Table 3.14), and the last season, i.e. 1997/98, when all N applications were doubled since N had no effect on yield for all previous seasons.
Wolmaransstad	Although yield data for six growing seasons (1991/92 - 1995/96 and 1997/98) at Wolmaransstad was recorded, relationships could only be established for the 1995/96 and 1997/98 seasons.
Koppies (2.24 m)	Although yield was recorded during three growing seasons, i.e. 1998/99 - 2000/01, only that of the 1999/2000 season was suitable for a significant relationship.
Ventersdorp	Data for one seasons only, 2001/02 was recorded and could be used for the establishment of relationships.
Viljoenskroon	During the first four seasons, i.e. 1993/94 until 1996/97 no or poor plant responses to P treatments were observed and therefore it was not included in relationships. An infestation of stalk borers during the 1994/95 season also affected yields badly (Smalberger, 2001). During the 2000/01 season maize was not planted on the same rows as for previous seasons, due to a mistake, and therefore this data was not included. Data from 1997/98 to 1999/00 was used.
Stilfontein (N x P)	Yield was obtained from the 1998/99 season, was affected by a severe infestation of stalk borers and therefore only data from the second season, i.e. 1999/2000, was used.
Stilfontein (P)	Although the same applies to yield during the 1998/99 season as to the NxP trial, yield measured during both seasons was not suitable for the establishment of significant relationships.
Heidelberg (N x P)	Soil sampling during the 1991/92 season was done only between maize rows, while samples collected during the 1992/93 season were incomplete. During both the 1993/94 and 1994/95 seasons, yield was badly affected by stalk borer infestations. Data from the last three seasons was suitable for the establishment of relationships.
Heidelberg (Lime x P)	Data for the first season, i.e. 1991/92, is incomplete and cannot be used, while no yield reaction was observed during the 1992/93 and 1994/95 seasons, due to lower rainfall occurrence and stalk borer infestations, although it cannot be verified. Thus data from four growing seasons, i.e. 1993/94 and 1995/96 until 1997/98, could be used for the establishment of relationships.
Athole	No yield was obtained during either the 1996/97 nor 1997/98 seasons, therefore no relationships could be established.
Belfast	No significant relationships could be established from data for the 1996/97 season.
Vrede	Due to poor yield response to P treatments, no significant relationships could be established for the 1996/97 and 1997/98 seasons.
Koppies (0.90 m)	During the 1999/2000 season poor yield response to P applications were observed, while yield for the 2000/01 season was damaged by a veld fire, theft and porcupines. Only data for the first growing season, i.e. 1998/99, was used for the establishment of relationships.
Dirkiesdorp	Data during the first two growing seasons was lost during rationalisation of the ARC-Grain Crops Institute and cannot be accounted for. During the 2000/01 season yield was negatively affected by fertilization due to low rainfall. Thus, data for three seasons, i.e. 1998/99 until 2001/02 was used for the establishment of relationships.

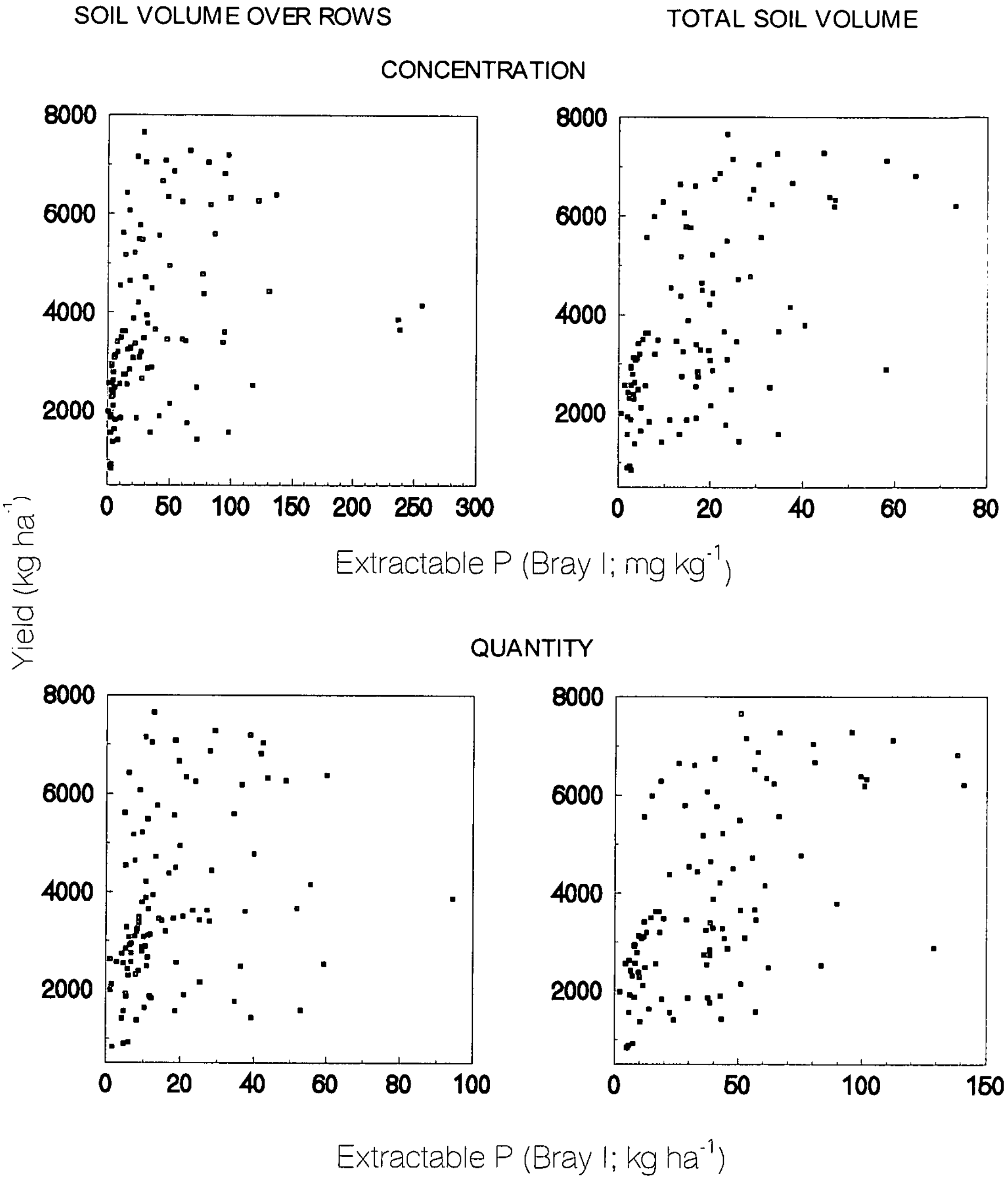

Figure 6.2 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield over localities (n = 105).

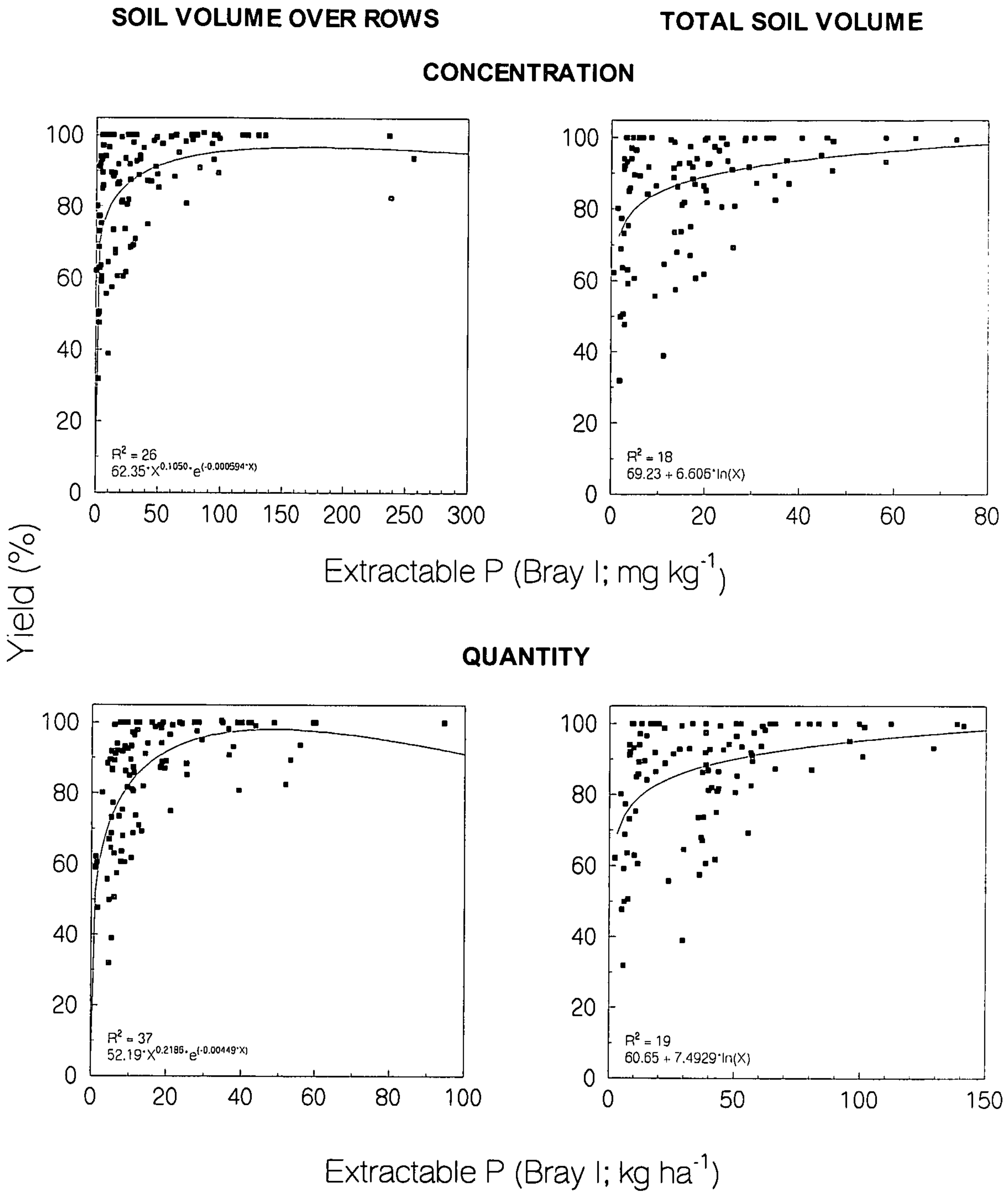

Figure 6.3 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield over localities (n = 105).

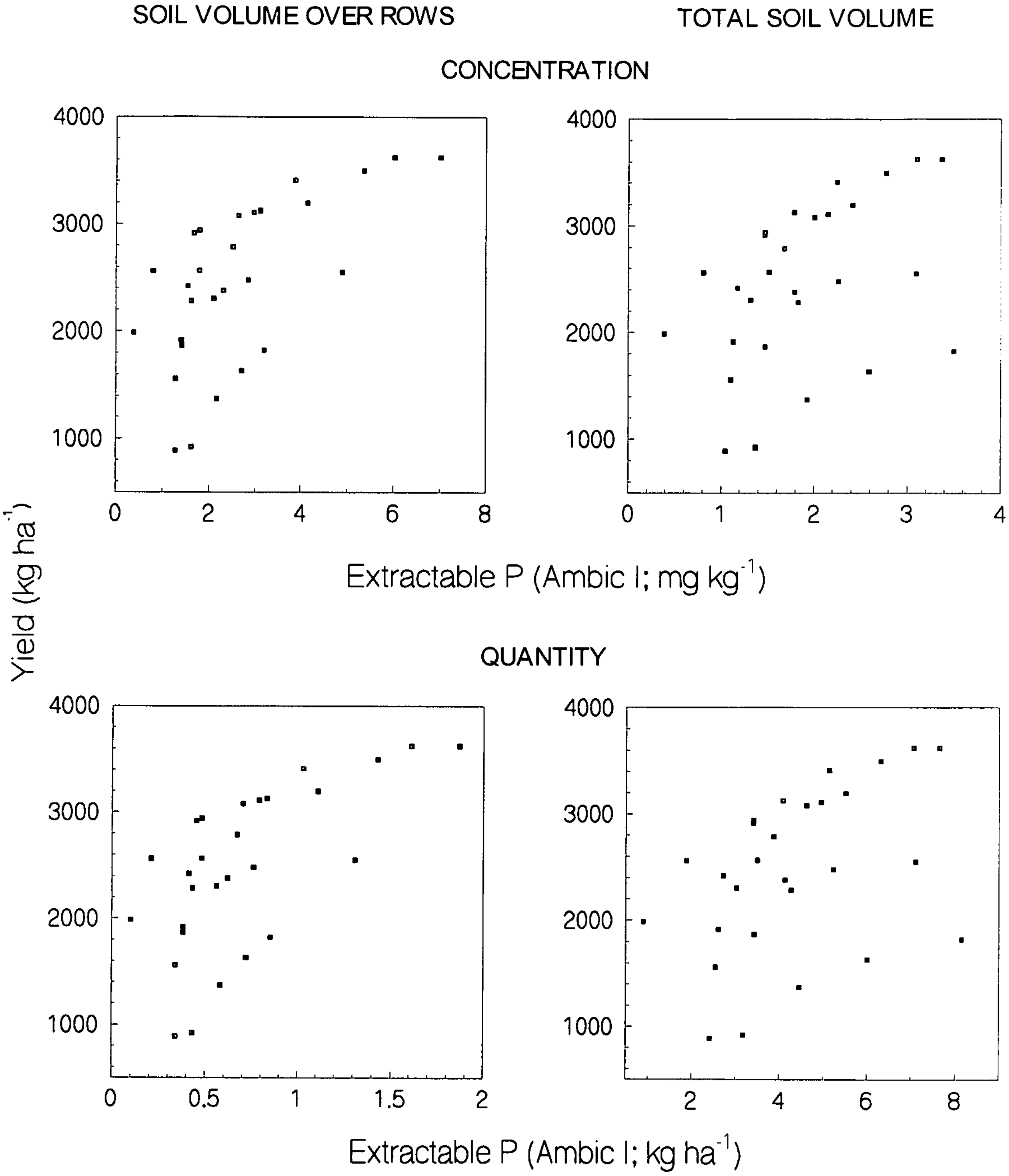

Figure 6.4 : Effects of extractable soil P (Ambic 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield for the 1989/90, 1990/91 and the 1992/93 until 1996/97 growing seasons at Lichtenburg (n = 28, consisting of 16 data points each).

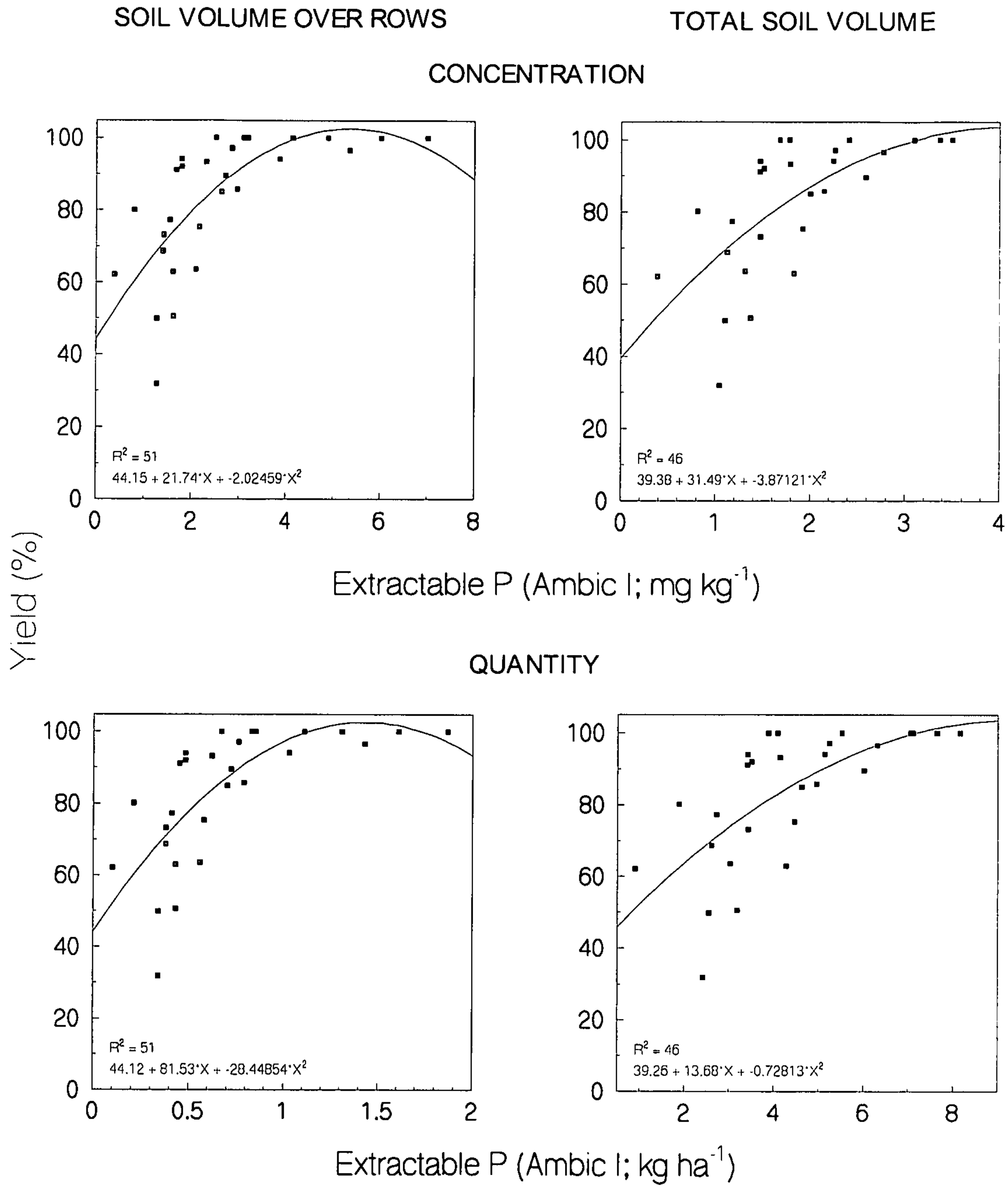

Figure 6.5 : Effects of extractable soil P (Ambic 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield for the 1989/90, 1990/91 and the 1992/93 until 1996/97 growing seasons at Lichtenburg (n = 28, consisting of 16 data points each).

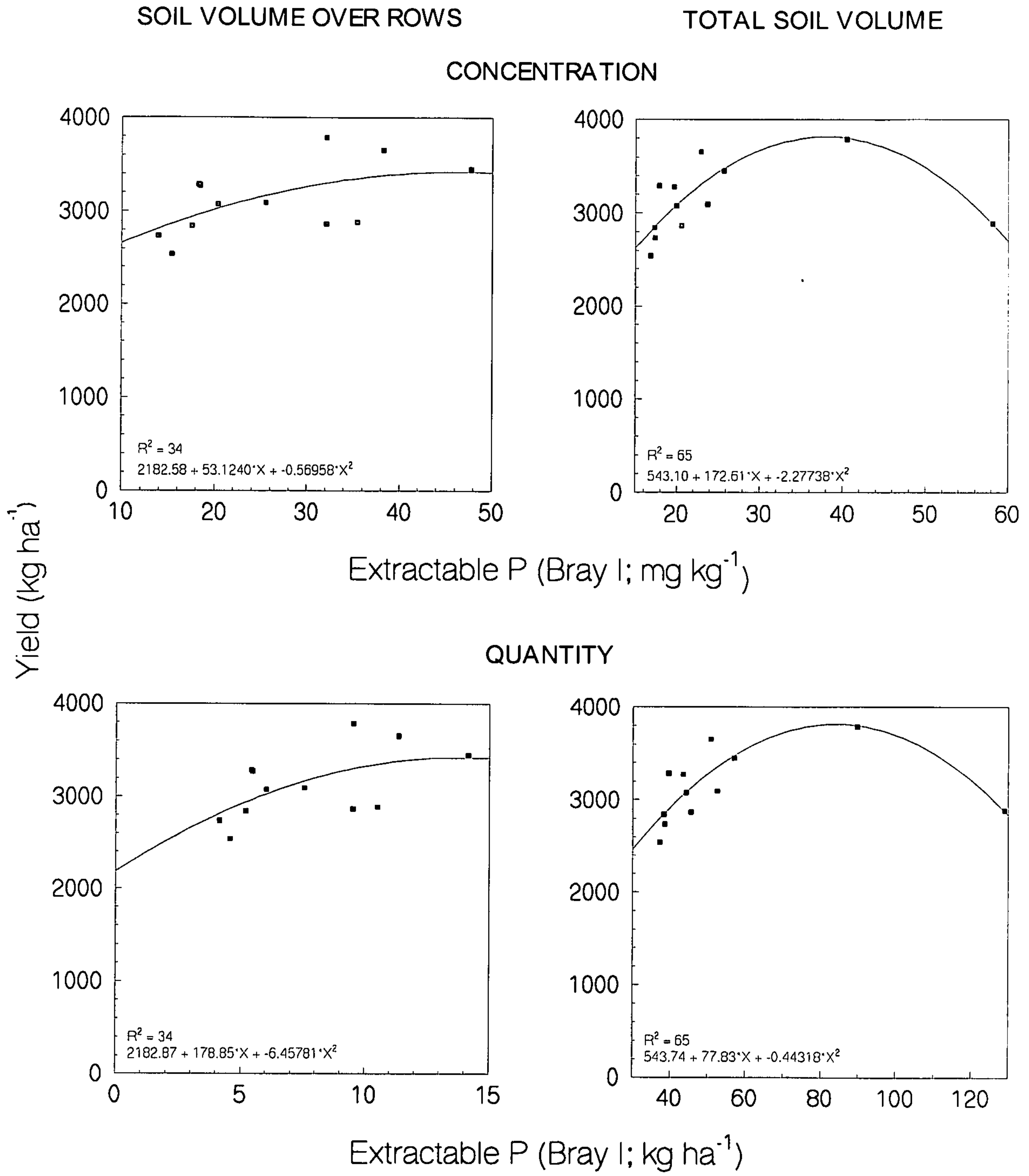

Figure 6.6 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield for the 1995/96 and 1996/97 growing seasons at Wolmaransstad (n = 12, consisting of 3 data points each).

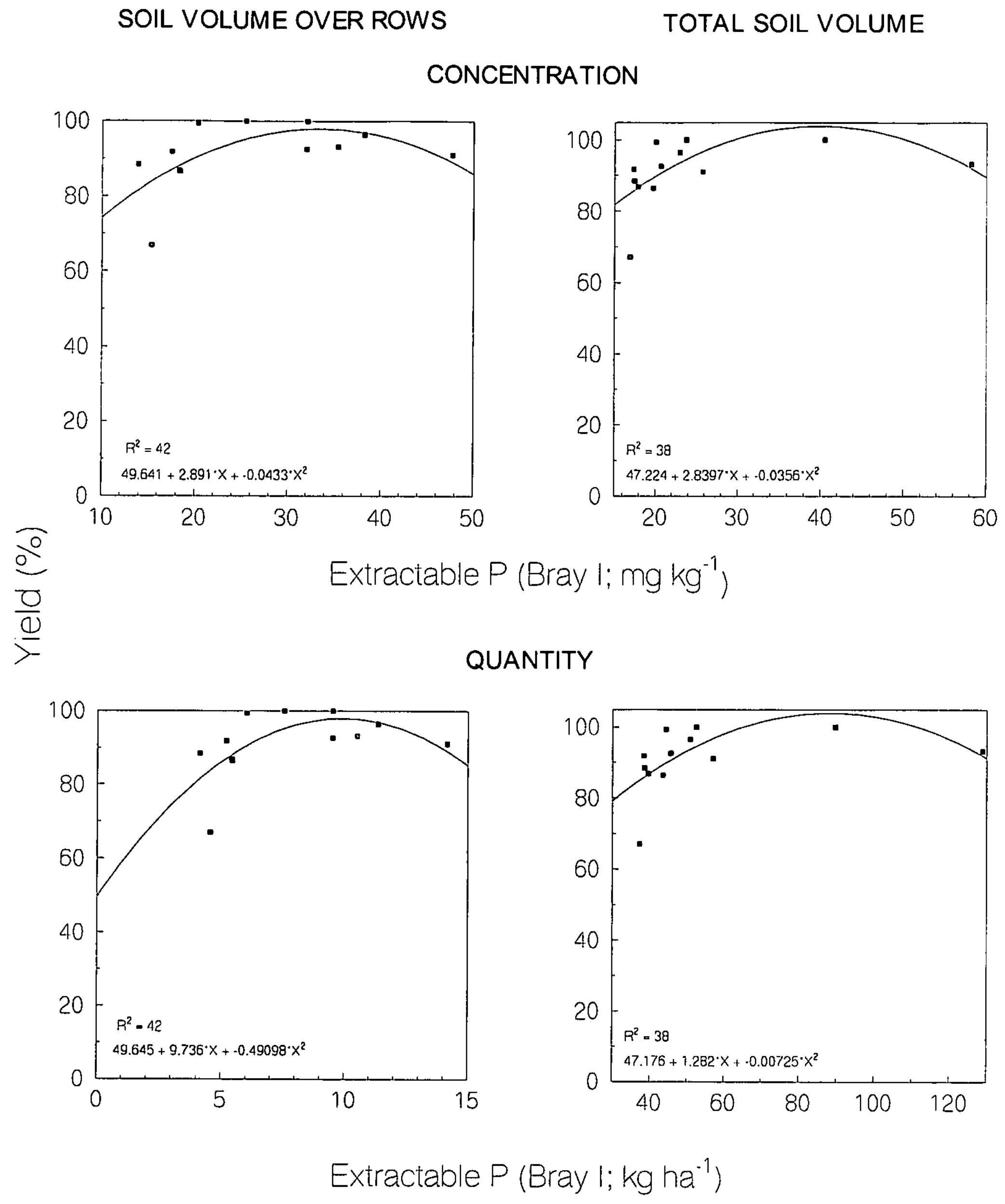

Figure 6.7 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield for the 1995/96 and 1996/97 growing seasons at Wolmaransstad (n = 12, consisting of 3 data points each).

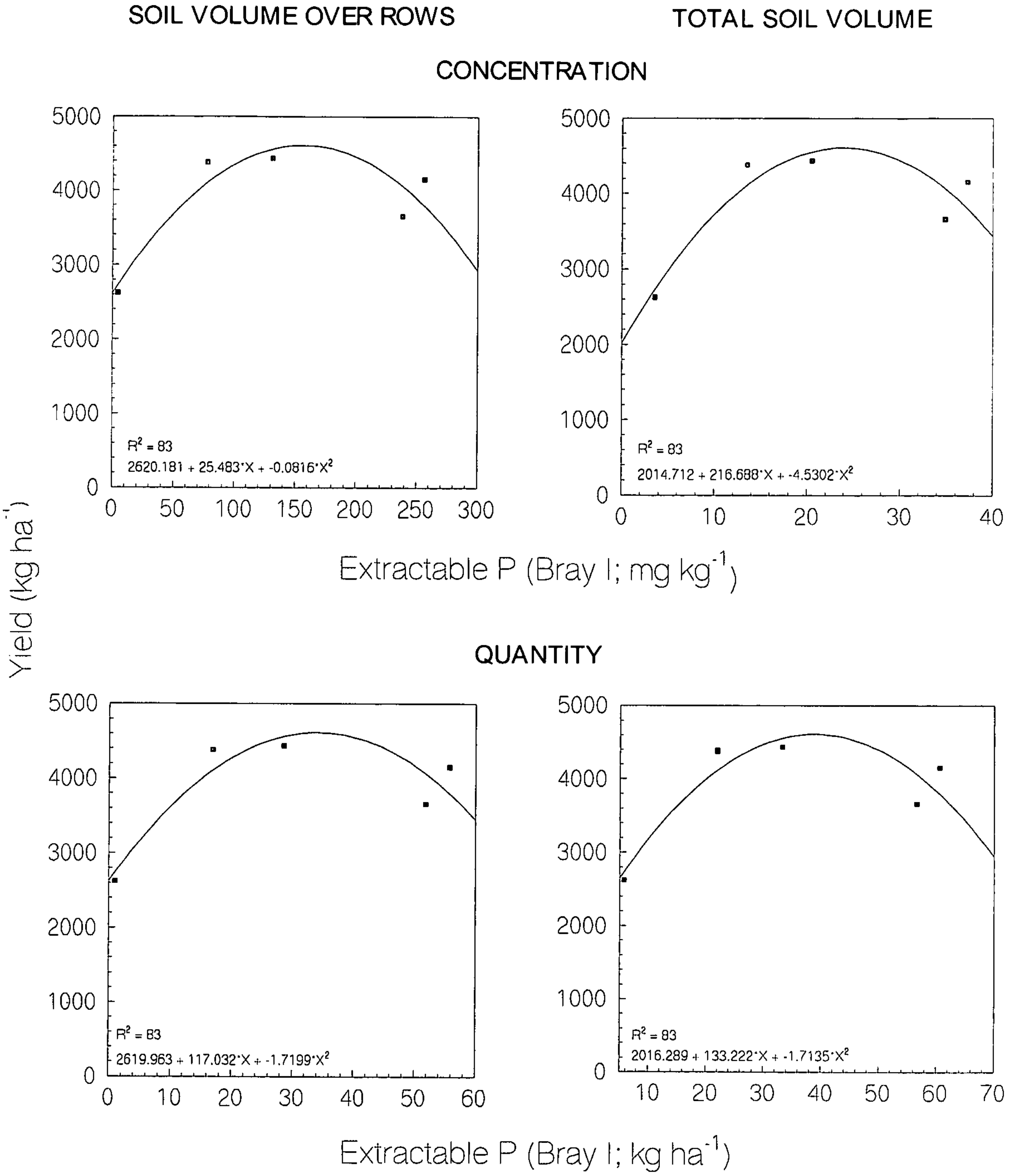

Figure 6.8 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield for the 1999/2000 growing season at Koppies (2.24 m trial; n = 5, consisting of 10 data points each).

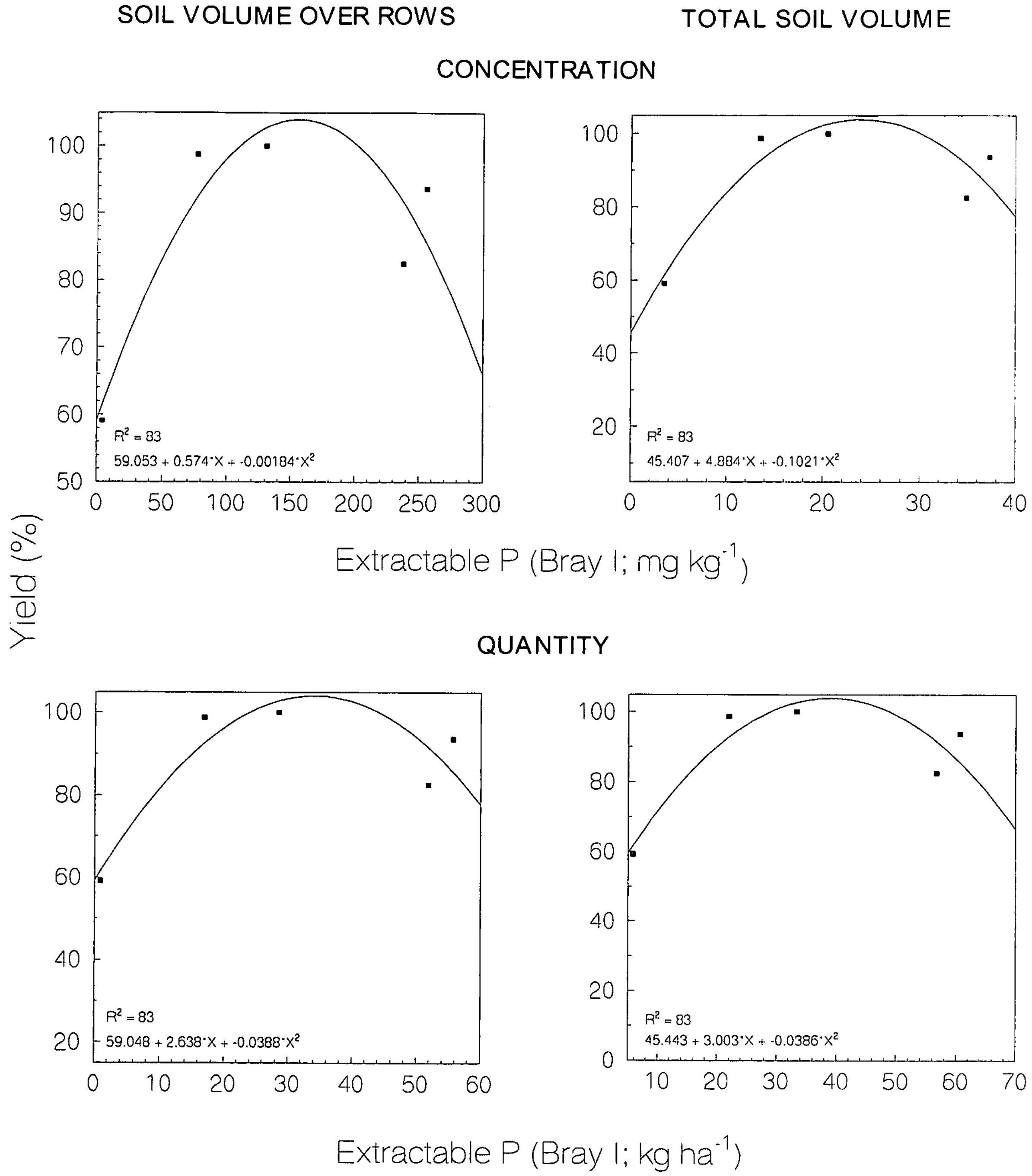

Figure 6.9 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield for the 1999/2000 growing season at Koppies (2.24 m trial; n = 5, consisting of 10 data points each).

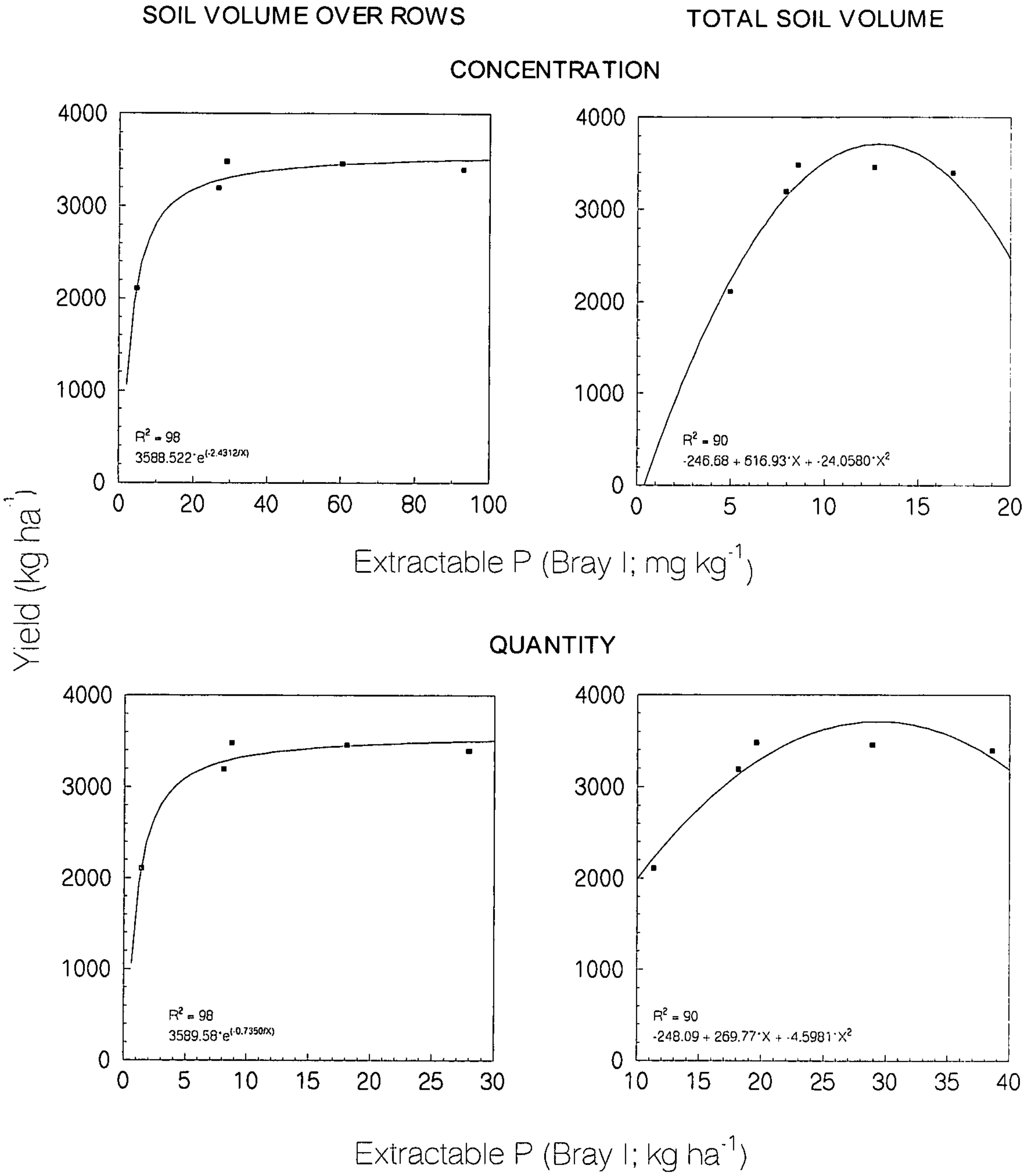

Figure 6.10 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield for the 2000/01 growing season at Ventersdorp (n = 5, consisting of 10 data points each).

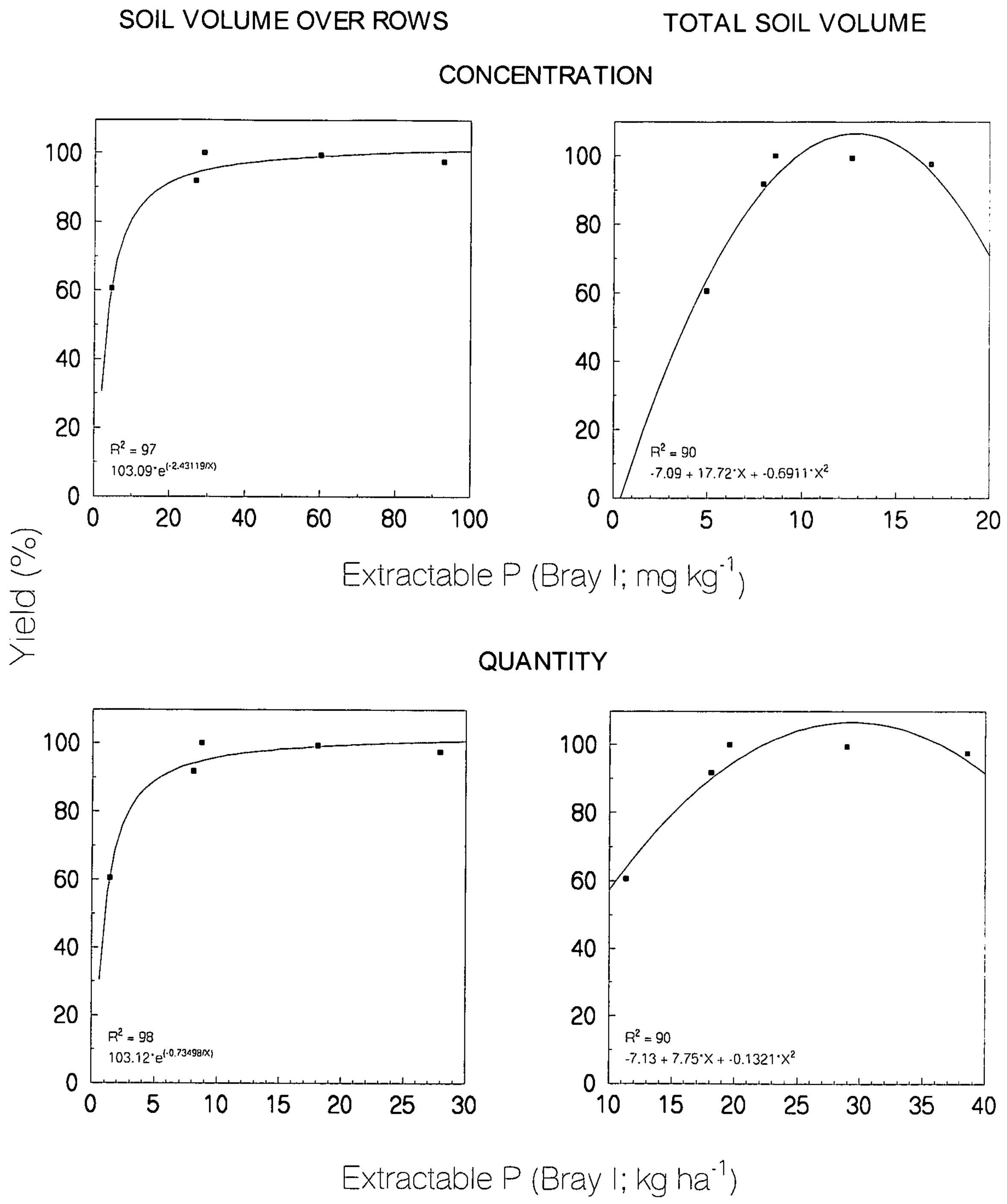

Figure 6.11 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield for the 2000/01 growing season at Ventersdorp (n = 5, consisting of 10 data points each).

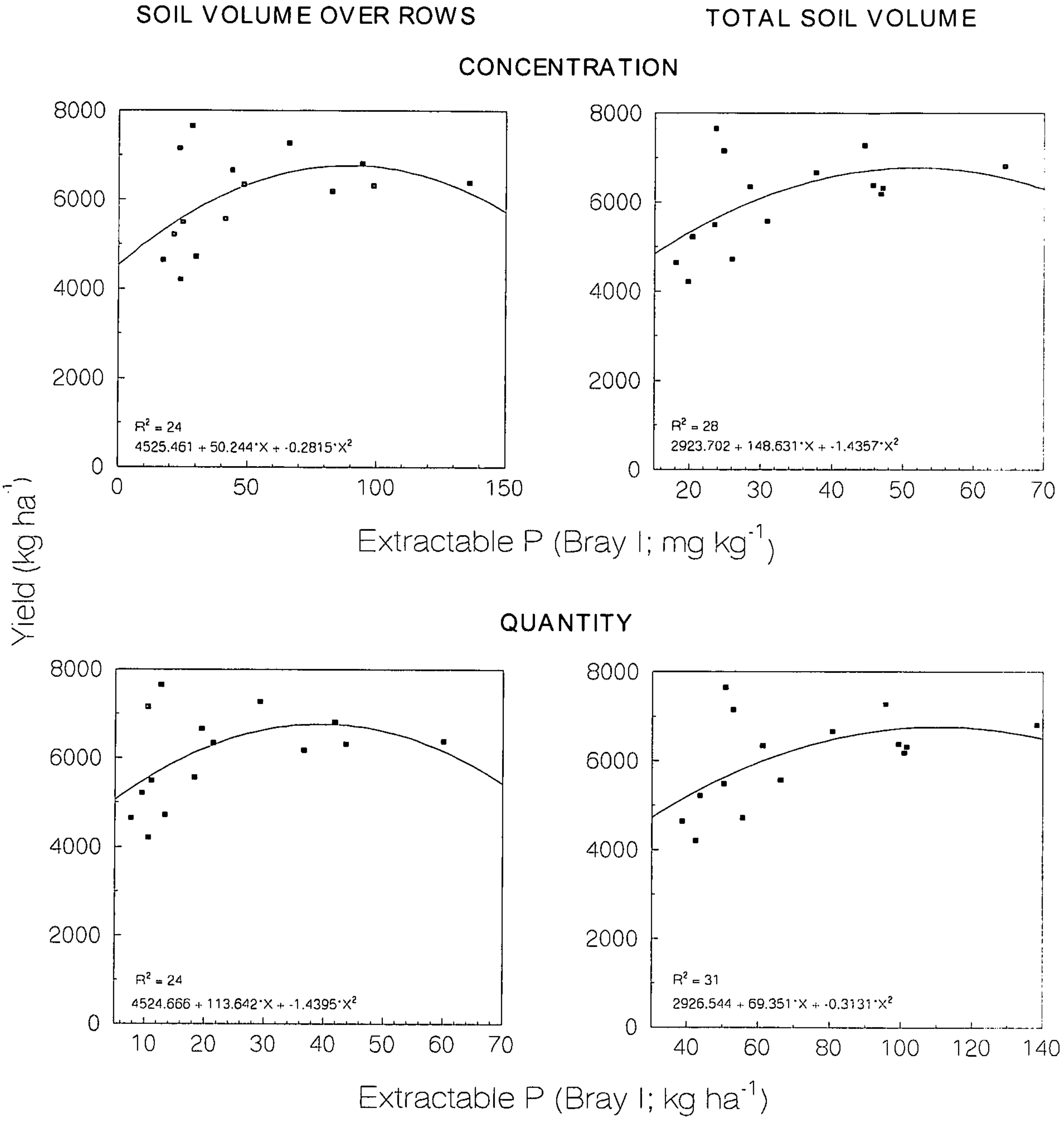

Figure 6.12 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield for the 1997/98 until the 1999/2000 growing seasons at Viljoenskroon (n = 15, consisting of 3 data points each).

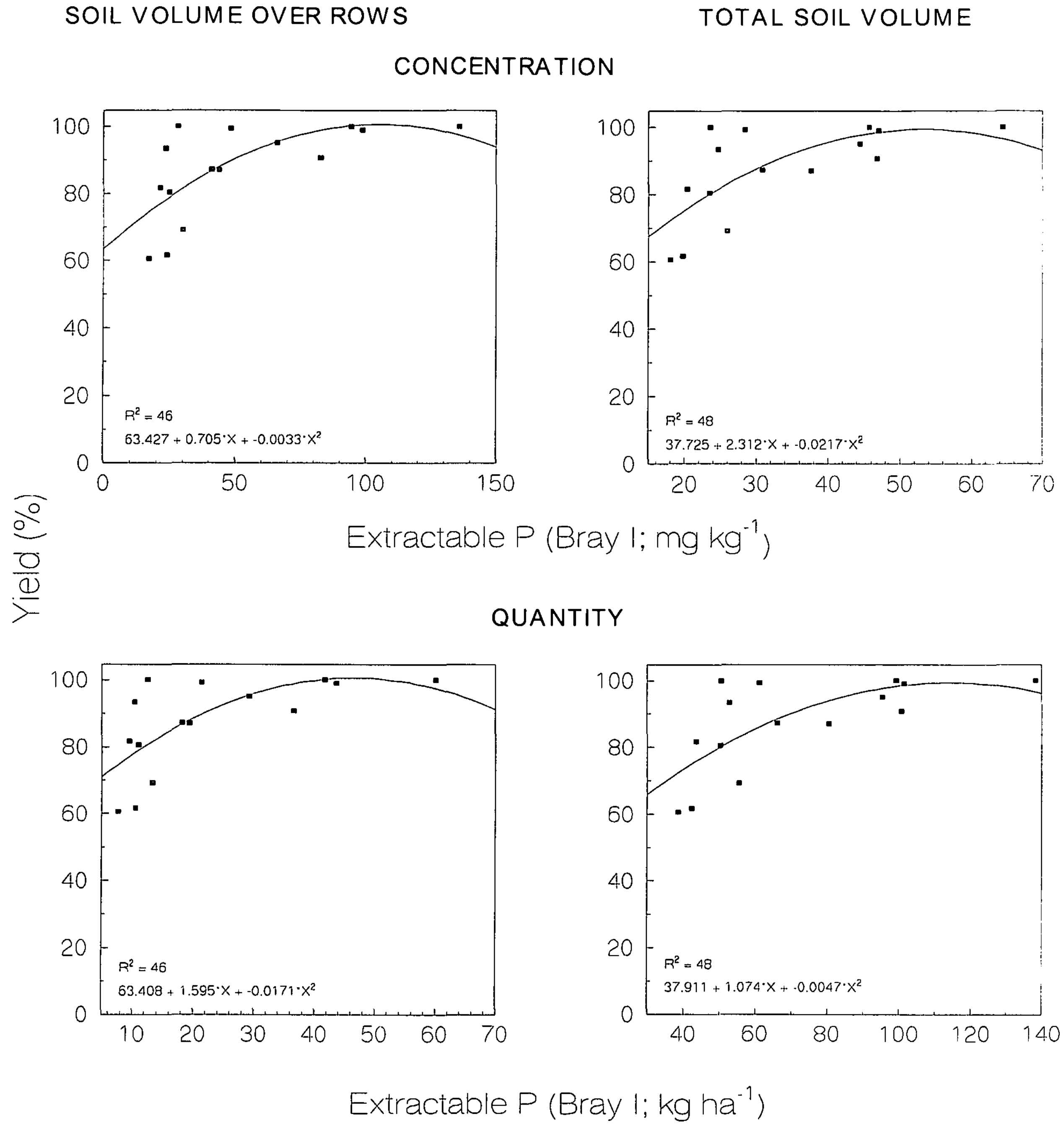

Figure 6.13 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield for the 1997/98 until the 1999/2000 growing seasons at Viljoenskroon (n = 15, consisting of 3 data points each).

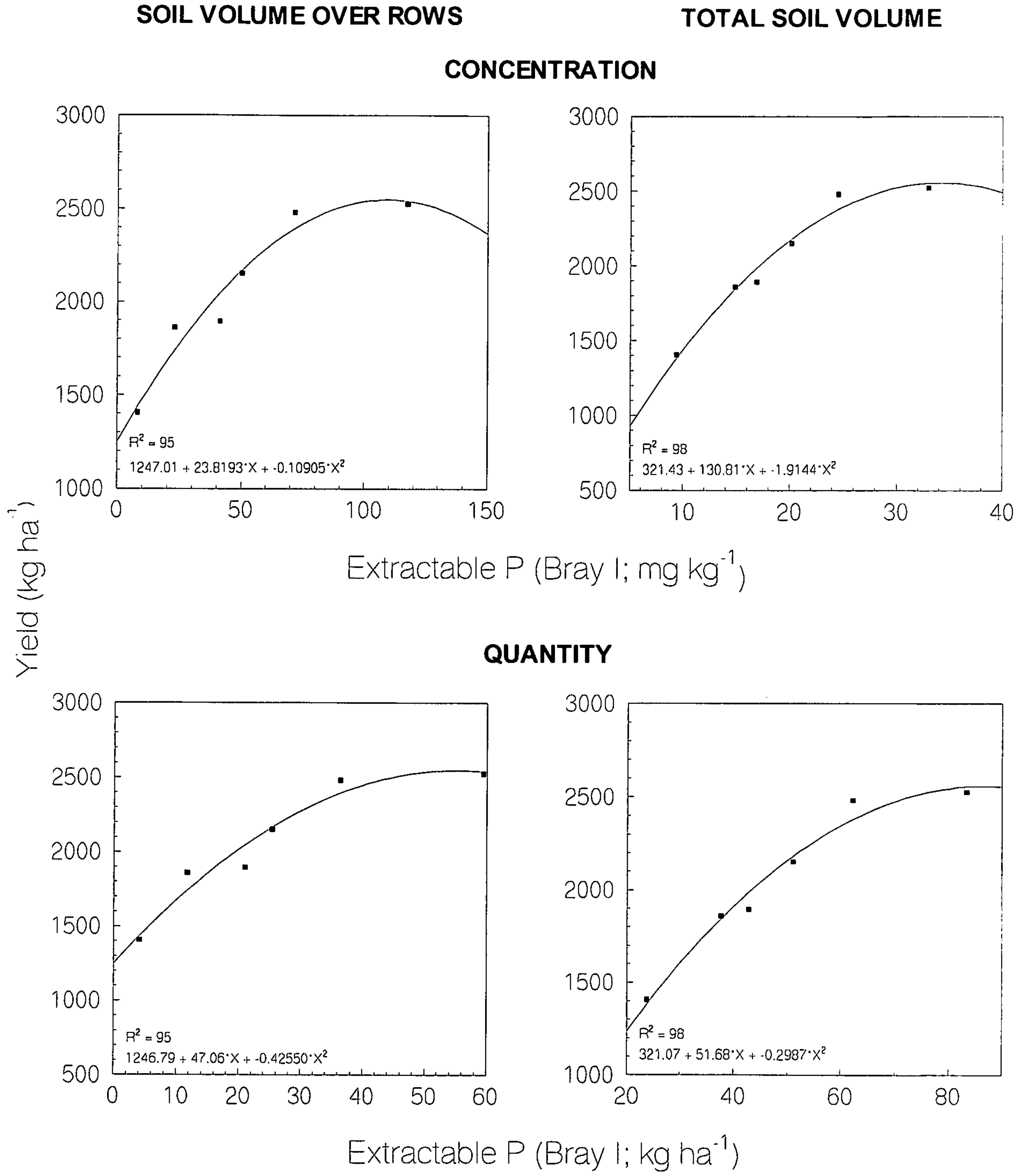

Figure 6.14 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield for the 1999/2000 growing season at Stilfontein (N x P trial; n = 6, consisting of 12 data points each).

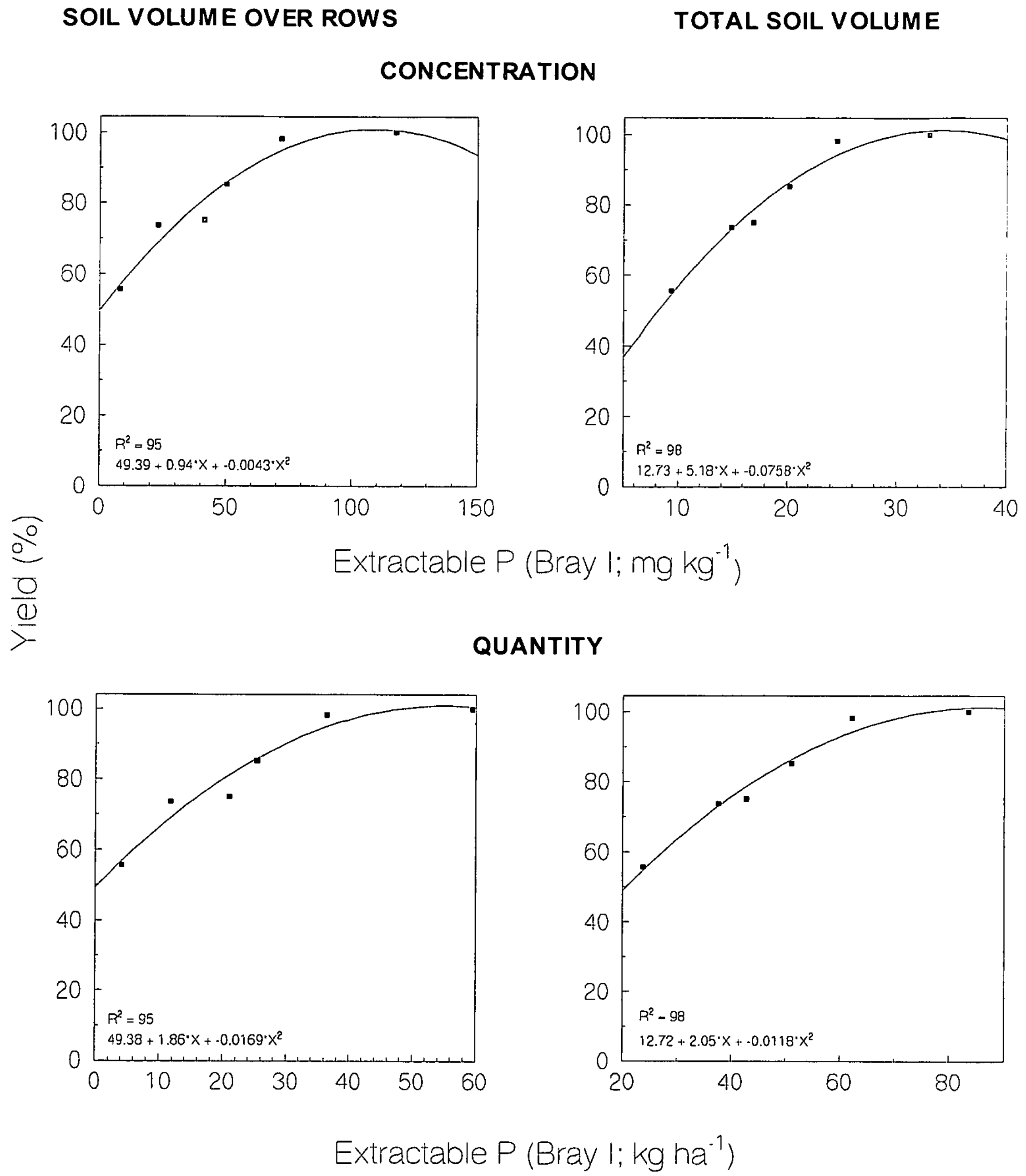

Figure 6.15 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield for the 1999/2000 growing season at Stilfontein (N x P trial; n = 6, consisting of 12 data points each).

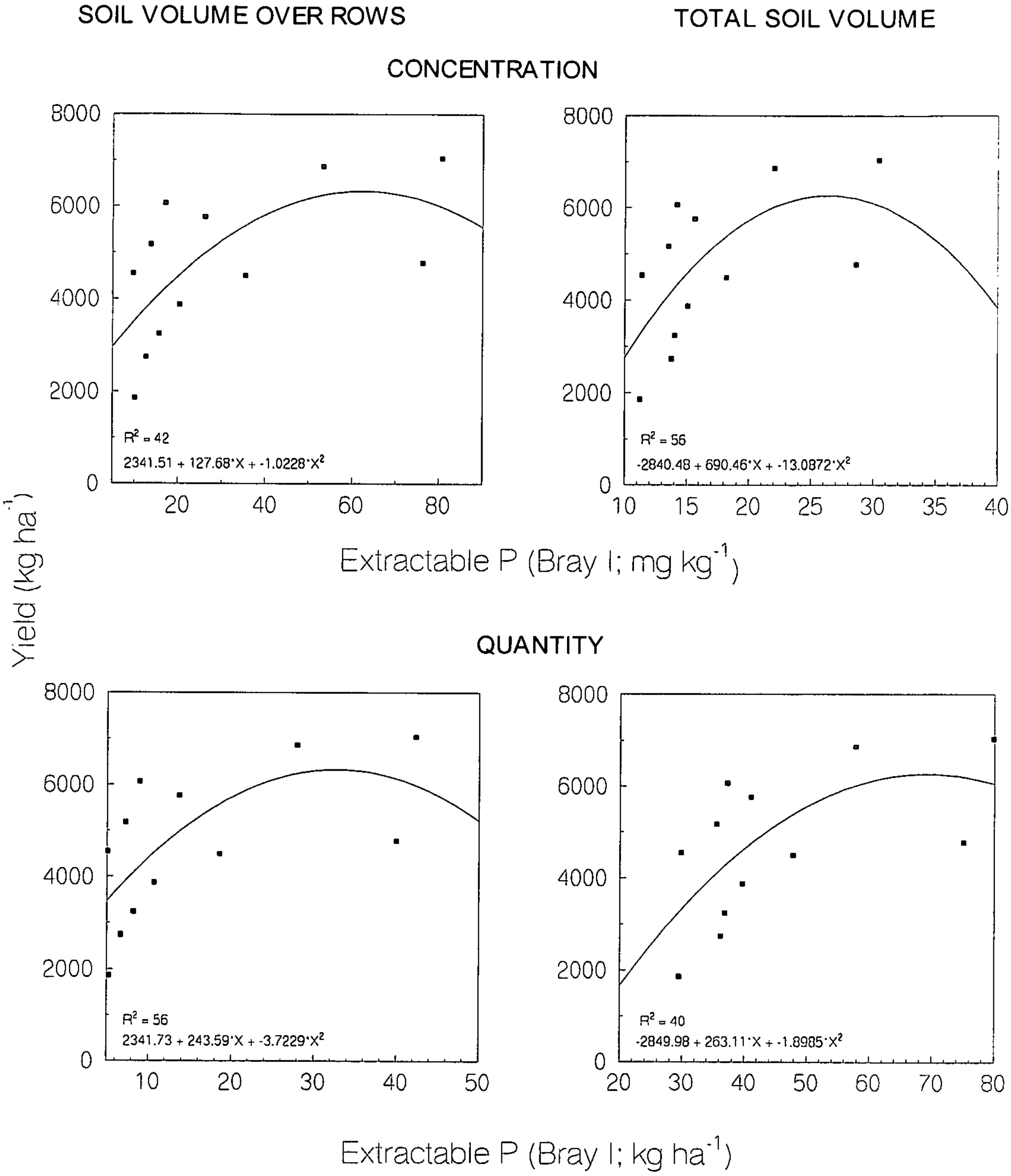

Figure 6.16 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield for the 1995/96 and 1996/97 growing seasons at Heidelberg (N x P trial; n = 12, consisting of 9 data points each).

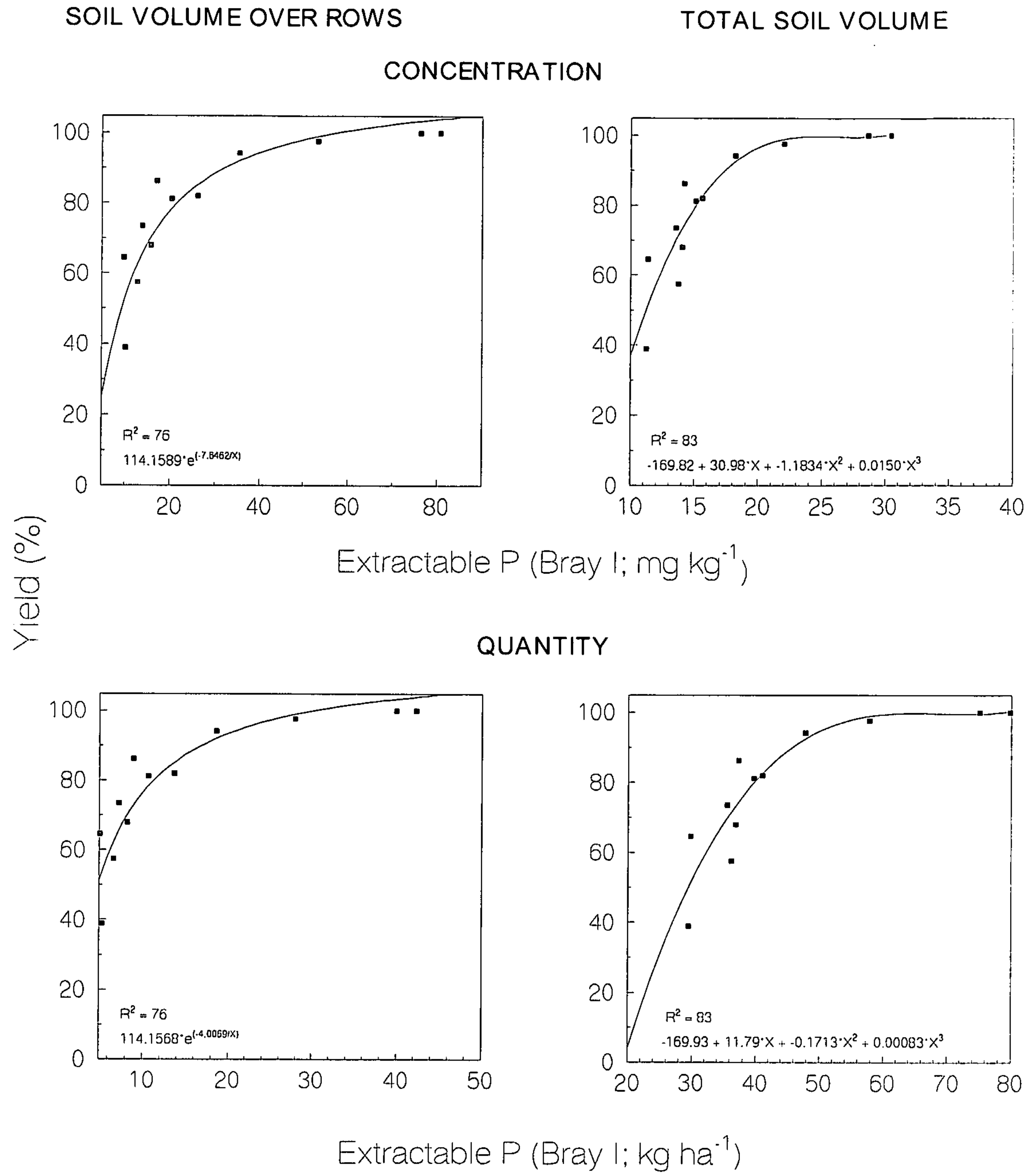

Figure 6.17 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield for the 1995/96 and 1996/97 growing seasons at Heidelberg (N x P trial; n = 12, consisting of 9 data points each).

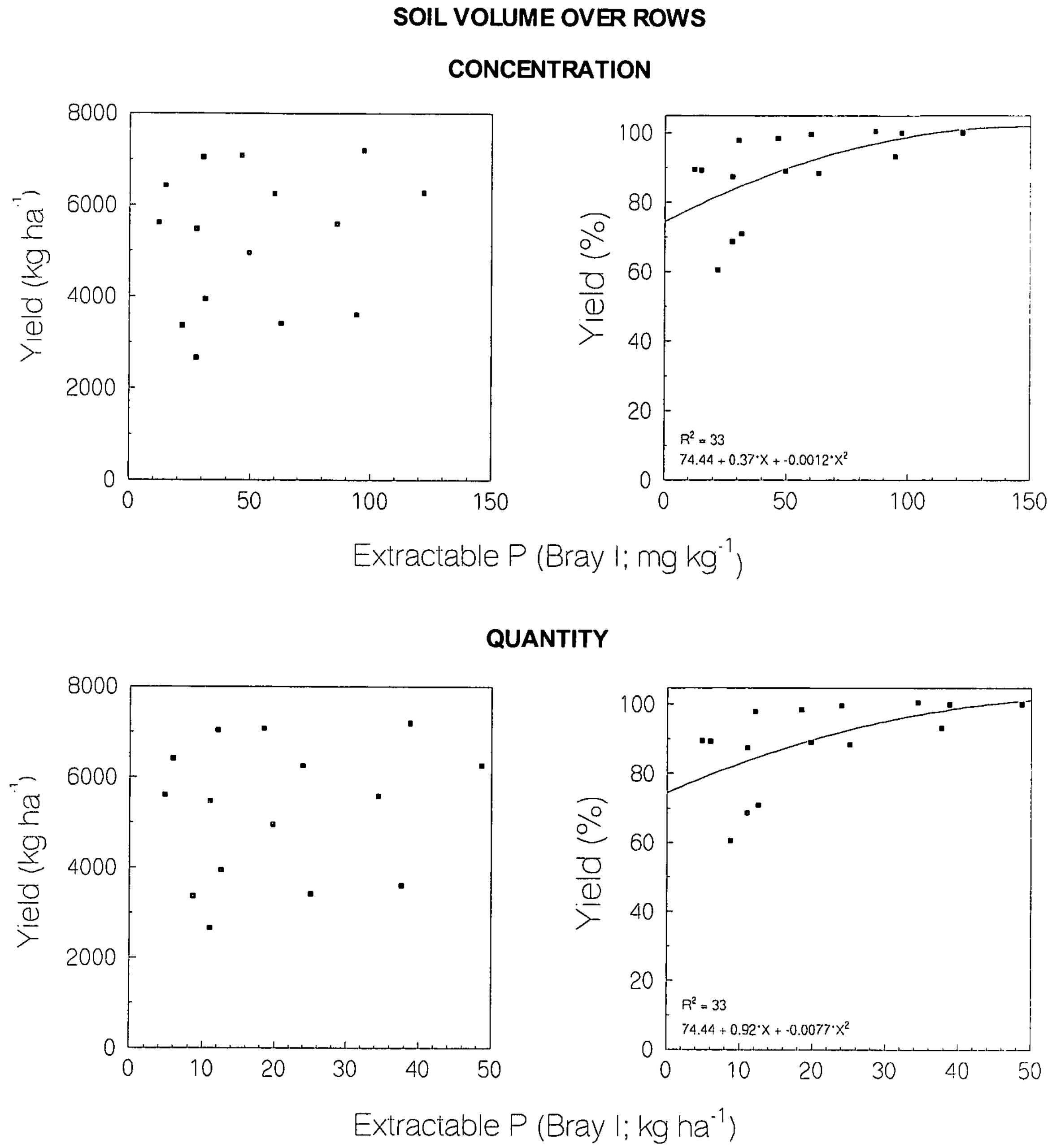

Figure 6.18 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows to a depth of 150 mm on absolute and relative yield for four growing seasons (1993/94 and 1995/96 until 1997/98) at Heidelberg (Lime x P trial; n = 15, consisting of 20 data points each).

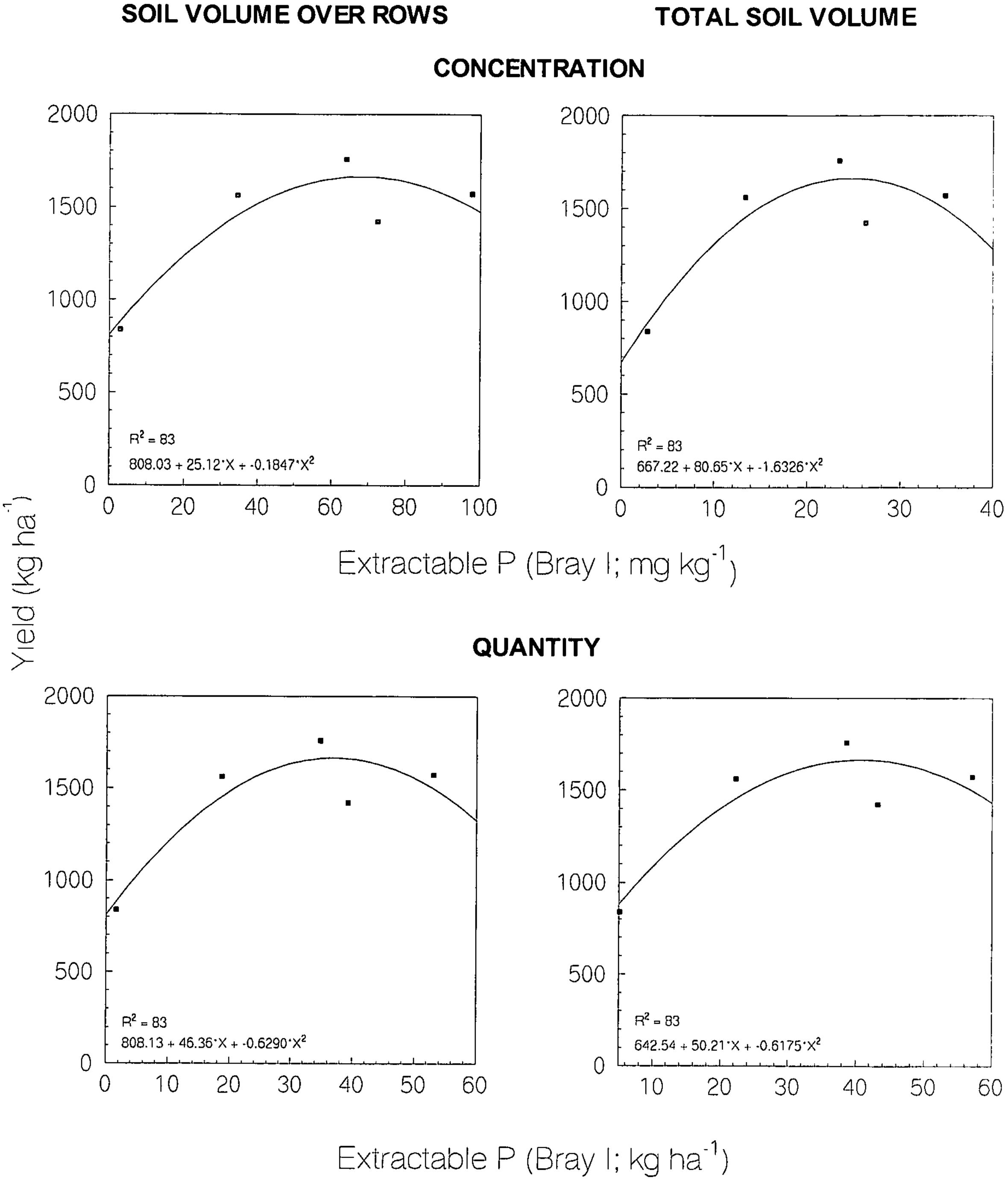

Figure 6.19 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on absolute yield for the 1998/99 growing season at Koppies (0.90 m trial; n = 5, consisting of 10 data points each).

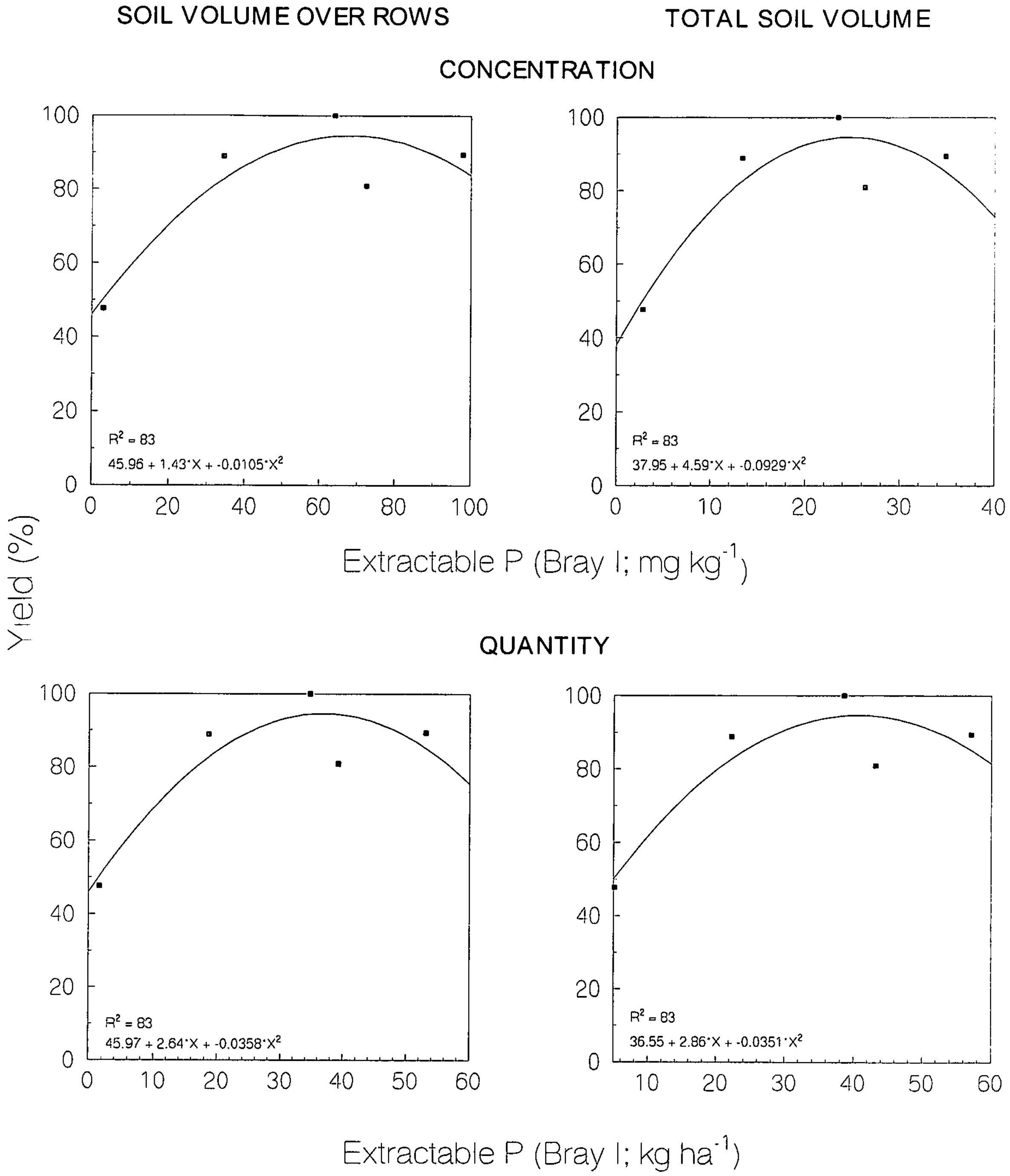

Figure 6.20 : Effects of extractable soil P (Bray 1) concentrations and quantities in a 300 mm wide strip over rows and in the total soil volume to a depth of 150 mm on relative yield for the 1998/99 growing season at Koppies (0.90 m trial; n = 5, consisting of 10 data points each).

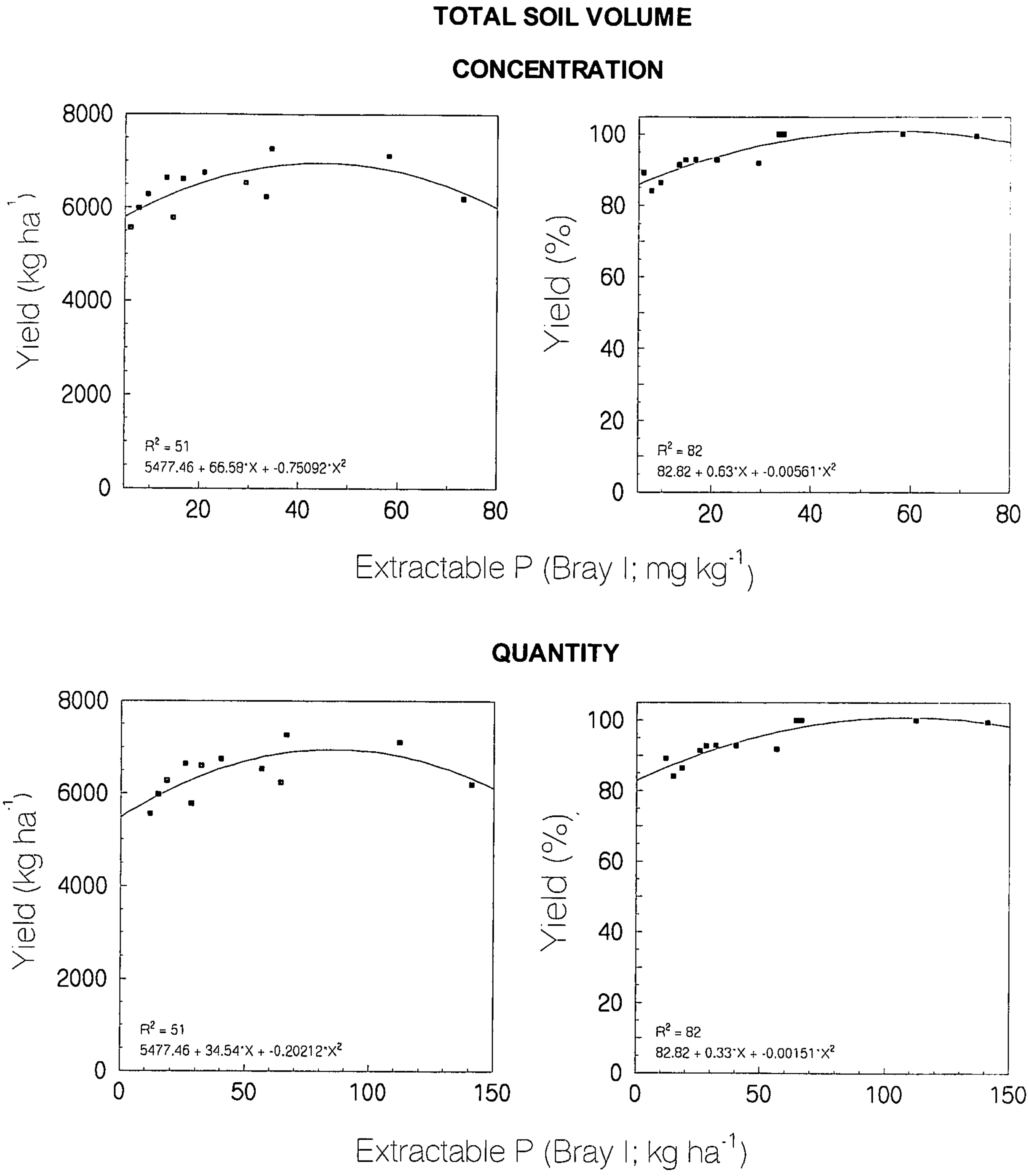

Figure 6.21 : Effects of extractable soil P (Bray 1) concentrations and quantities in the total soil volume to a depth of 150 mm on absolute and relative yield for three growing seasons (1998/99, 1999/2000 and 2001/02) at Dirkiesdorp (n = 12, consisting of 4 data points each).

As mentioned earlier in Section 6.2 the threshold extractable P concentrations and quantities (Ambic 1 for Lichtenburg and Bray 1 for the other localities) that were needed in the soil volume over the rows and in the total soil volumes to obtain 90 and 95 % relative yields were derived from the equations presented in Figures 6.4 to 6.21 and then transposed to equivalent Bray 1 (Lichtenburg) and Ambic 1 (other localities) values. All these extractable P values are summarized in Table 6.3. Large differences in threshold extractable P values between localities for similar relative yields, soil volumes and extraction methods were shown (Table 6.3).

As explained in Section 5.2 the row width must be accounted for when threshold P concentrations of soil volumes over rows are compared, which is not the case with threshold P quantities. The threshold P concentrations and quantities in total soil volumes can be compared regardless of the row width.

Threshold extractable P values established in this study cannot really be compared with findings of other researchers, mainly because P fertilization was broadcast in other studies and soil sampling was also done differently as already explained. Even comparison with results of Landman (1995) was impossible since he related relative biomass and not relative grain yield to extractable soil P values although he used the same soil sampling procedure.

6.3.3 Threshold soil phosphorus values and properties

The threshold soil P values given in Table 6.3 were related to different soil properties by means of simple and multiple regression. As a result of differences in row widths the threshold P concentrations for soil volumes over rows cannot be used in this exercise. Soil properties that were used in these regressions are those recorded in the topsoil during characterization of the soil as described in Section 3.2. In general the multiple regressions gave disappointingly low R^2-values and were therefore ignored. However, some soil properties explain the variation in threshold soil P values reasonably well through simple regressions as shown in Table 6.4

Soil properties which explained the variation in threshold soil P values most consistently were in decreasing order the degree of leaching based on clay content (DL_c), silt-plus-clay content, organic C content and silt content. However, the emphasis in this discussion is on the particle size fractions and not the degree of leaching since it is more likely that the chemical soil properties were affected by the treatments than the physical soil properties as explained in Section 3.2. In future a thorough investigation into the relationships between degree of leaching and threshold soil P which should also include the effect of this parameter on the P requirement of soils is warranted (Section 5.3.3).

Surprisingly, clay content had no significant effect on the threshold P quantity in the soil volume over rows (Table 6.4). However, the threshold P quantity in the soil volume over rows was significantly related to the silt content (Table 6.4). By excluding data from Stilfontein (N x P) and Heidelberg (Lime x P) silt content was related to P threshold (Figure 6.22). Since no explanation can be given for the fact that silt content explained the variation in this particular case better than the clay content, the equations given in Figure 6.22 should be validated thoroughly before they are recommended for general use.

Table 6.3 : Extractable P concentrations and quantities required in soil volumes over rows and total soil volumes to a depth of 150 mm deep to obtain 90 or 95 % relative yields

Locality	90 % relative yield								95 % relative yield							
	Soil volume over rows				Total soil volume				Soil volume over rows				Total soil volume			
	Ambic 1		Bray 1		Ambic 1		Bray 1		Ambic 1		Bray 1		Ambic 1		Bray 1	
	C	Q	C	Q	C	Q	C	Q	C	Q	C	Q	C	Q	C	Q
Lichtenburg	3	1	6[1]	2[4]	2	5	4[1]	9[4]	4	1	8[1]	2[4]	3	6	6[1]	14[4]
Wolmaransstad	10[2]	3[3]	20	6	10[2]	23[3]	20	45	14[2]	4[3]	25	8	13[2]	29[3]	24	53
Koppies (2.24 m)	35[2]	8[3]	69	15	5[2]	8[3]	12	20	45[2]	10[3]	87	19	7[2]	11[3]	15	24
Ventersdorp	13[2]	4[3]	18	5	5[2]	11[3]	8	18	24[2]	7[3]	30	9	6[2]	14[3]	9	20
Viljoenskroon	39[2]	17[3]	49	22	25[2]	55[3]	33	70	52[2]	23[3]	64	29	30[2]	67[3]	39	84
Stilfontein (N x P)	43[2]	22[3]	60	30	15[2]	38[3]	22	55	52[2]	26[3]	73	37	17[2]	43[3]	25	63
Heidelberg (N x P)	19[2]	10[3]	32	17	8[2]	21[3]	17	45	26[2]	14[3]	42	22	9[2]	25[3]	19	50
Heidelberg (Lime x P)	46[2]	18[3]	50	20	-	-	-	-	67[2]	27[3]	73	30	-	-	-	-
Koppies (0.90 m)	24[2]	13[3]	47	25	8[2]	13[3]	18	29	35[2]	19[3]	68	37	12[2]	19[3]	25	41
Dirkiesdorp	-	-	-	-	8[2]	16[3]	13	25	-	-	-	-	6[2]	31[3]	25	47
Over all localities[5]	-[6]	-[6]	42	17	-[6]	-[6]	23	50	-[6]	-[6]	94	27	-[6]	-[6]	50	98

C = Concentration (mg kg^{-1}) and Q = Quantity (kg ha^{-1}); [1] - Bray 1 concentrations calculated from Bray 1 versus Ambic 1 relationships (Table 4.4); [2] - Ambic 1 concentrations calculated from Ambic 1 versus Bray 1 relationships (Table 4.4); [3] - Ambic 1 quantities calculated from Ambic 1 concentrations; [4] - Bray 1 quantities calculated from Bray 1 concentrations; [5] - Dirkiesdorp was not included in relationships for soil volumes over rows, while Heidelberg (Lime x P) was not included in relationships for total soil volumes; [6] - Ambic 1 values not determined or calculated

Table 6.4 : Explanation of variation (R^2), correlation coefficients (r) and probabilities (*P*) for the simple regression analyses done between threshold soil P values and soil properties

Soil properties	**Localities**	**Ambic 1**									**Bray 1**								
		Volume over rows			**Total soil volume**						**Volume over rows**			**Total soil volume**					
		Q			**C**			**Q**			**Q**			**C**			**Q**		
		R^2 (%)	**r**	***P***	**R^2 (%)**	**r**	***P***	**R^2 (%)**	**r**	***P***	**R^2 (%)**	**r**	***P***	**R^2 (%)**	**r**	***P***	**R^2 (%)**	**r**	***P***
90 % Relative yield threshold																			
Clay (%)	All	2	-0.15	ns	30	0.55	ns	35	0.59	ns	8	0.28	ns	20	0.44	ns	28	0.53	ns
Silt (%)	All	45	-0.67	0.0478	25	0.50	ns	13	0.36	ns	49	-0.70	0.0351	28	0.53	ns	10	0.31	ns
Silt + Clay (%)	All	15	0.39	ns	65	0.81	0.0084	66	0.81	0.0075	4	0.19	ns	43	0.64	0.0546	47	0.69	0.0414
Organic C (%)	All	14	0.37	ns	46	0.68	0.0444	45	0.67	0.0489	10	0.31	ns	44	0.66	0.0512	44	0.66	0.0529
1:1 + 2:1 Clay (%)	All	13	-0.37	ns	9	-0.30	ns	3	-0.16	ns	20	0.45	ns	7	-0.26	ns	3	-0.16	ns
CBD - Fe (%)	All	15	0.38	ns	15	0.39	ns	31	0.55	ns	4	0.21	ns	6	0.24	ns	15	-0.38	ns
CBD - Al (%)	All	42	0.64	ns	18	0.42	ns	15	0.38	ns	32	0.57	ns	12	0.35	ns	12	0.34	ns
CEC (cmol$_c$kg^{-1})	All	8	-0.28	ns	30	-0.55	ns	44	-0.67	0.0499	3	0.18	ns	18	-0.43	ns	33	-0.58	ns
Degree of leaching (clay)[1]	All	52	0.72	0.0275	63	0.80	0.0103	70	0.84	0.0047	42	0.65	0.0594	48	0.69	0.0381	58	0.76	0.0178
95 % Relative yield threshold																			
Clay (%)	All	1	-0.11	ns	32	0.56	ns	28	0.53	ns	8	0.28	ns	8	0.27	ns	18	0.43	ns
Silt (%)	All	43	-0.66	0.0539	32	0.57	ns	15	0.39	ns	49	-0.70	0.0346	31	0.56	ns	12	0.35	ns
Silt + Clay (%)	All	18	0.42	ns	64	0.80	0.0096	59	0.77	0.0150	4	0.20	ns	28	0.52	ns	40	0.63	0.0691
Organic C (%)	All	19	0.43	ns	53	0.72	0.0272	40	0.63	0.0690	16	0.40	ns	28	0.53	ns	34	0.59	ns
1:1 + 2:1 Clay (%)	All	13	-0.36	ns	4	-0.21	ns	6	-0.25	ns	19	0.43	ns	8	-0.27	ns	2	-0.15	ns
CBD - Fe (%)	All	-	-	-	5	0.21	ns	25	0.50	ns	4	0.19	ns	4	0.20	ns	15	-0.39	ns
CBD - Al (%)	All	-	-	-	8	-0.28	ns	22	0.47	ns	40	0.63	0.0696	12	0.35	ns	11	0.34	ns
CEC (cmol$_c$kg^{-1})	All	12	-0.34	ns	20	-0.45	ns	40	-0.63	0.0681	8	-0.28	ns	11	-0.33	ns	29	-0.53	ns
Degree of leaching (clay)[1]	All	41	-0.64	0.0653	43	0.66	0.0547	71	0.84	0.0045	30	-0.55	ns	37	0.61	0.0822	46	0.67	0.0462

C = Concentration (mg kg^{-1}) and Q = Quantity (mg kg^{-1}); [1] Degree of leaching = [((Ca/200 + K/391 + Mg/122 + Na/230; cmol$_c$ kg soil^{-1})*100)/Clay (%)]

As shown in Table 6.4 the silt-plus-clay content explained variation in threshold P concentration and quantity in the total soil volume similarly and significantly (R^2-values ranged from 59 to 65 % for Ambic 1 and from 28 to 47 % for Bray 1). However, when data from the Lichtenburg and Ventersdorp trials were excluded the explanation of variation increased substantially (R^2-values ranged from 85 to 91 % for Ambic 1 and from 70 to 92 % for Bray 1 in Figures 6.23 and 6.24, respectively).

The exclusion of data from the Lichtenburg and Ventersdorp trials can be justified by findings of Katušić, Manson & Miles (1995) who reported that the extraction of P with both the Ambic 1 and Bray 1 methods is hampered by the presence of lime in soils. The soil at Lichtenburg belonged to the Baden family of the Montagu form which has a neocarbonate B horizon (Appendix 3.1). Thus the topsoil showed a high pH(H_2O) of 8.05 implicating free lime as was confirmed by strong effervescence with 10 % HCl solution. The soil at the Ventersdorp trial belonged to the Hayfield family of the Hutton form and was heavily limed a month before planting with dolomite lime at a rate of 15 t ha^{-1} to reduce acid saturation from 65 to 23 % (Appendix 3.1). Some lime could still have been present in the topsoil during sampling although not confirmed by effervescence with 10 % HCl solution. Thus, it appears that even traces of lime in soil may have a significant influence on P extraction by the Ambic 1 and Bray 1 methods, an aspect that warrants further research.

Extractable P threshold declined with an increase in silt-plus-clay content (Figures 6.23 for Ambic 1 and 6.24 for Bray 1). Therefore, based on the silt-plus-clay content range for soils used, the concentrations and quantities of extractable P required in the total soil volume for either 90 or 95 % relative yield were calculated using the equations in Figures 6.23 and 6.24. These derivations are presented in Table 6.5 and can be used in phosphorus fertilization recommendations for maize when cultivated on soils containing no traces of lime.

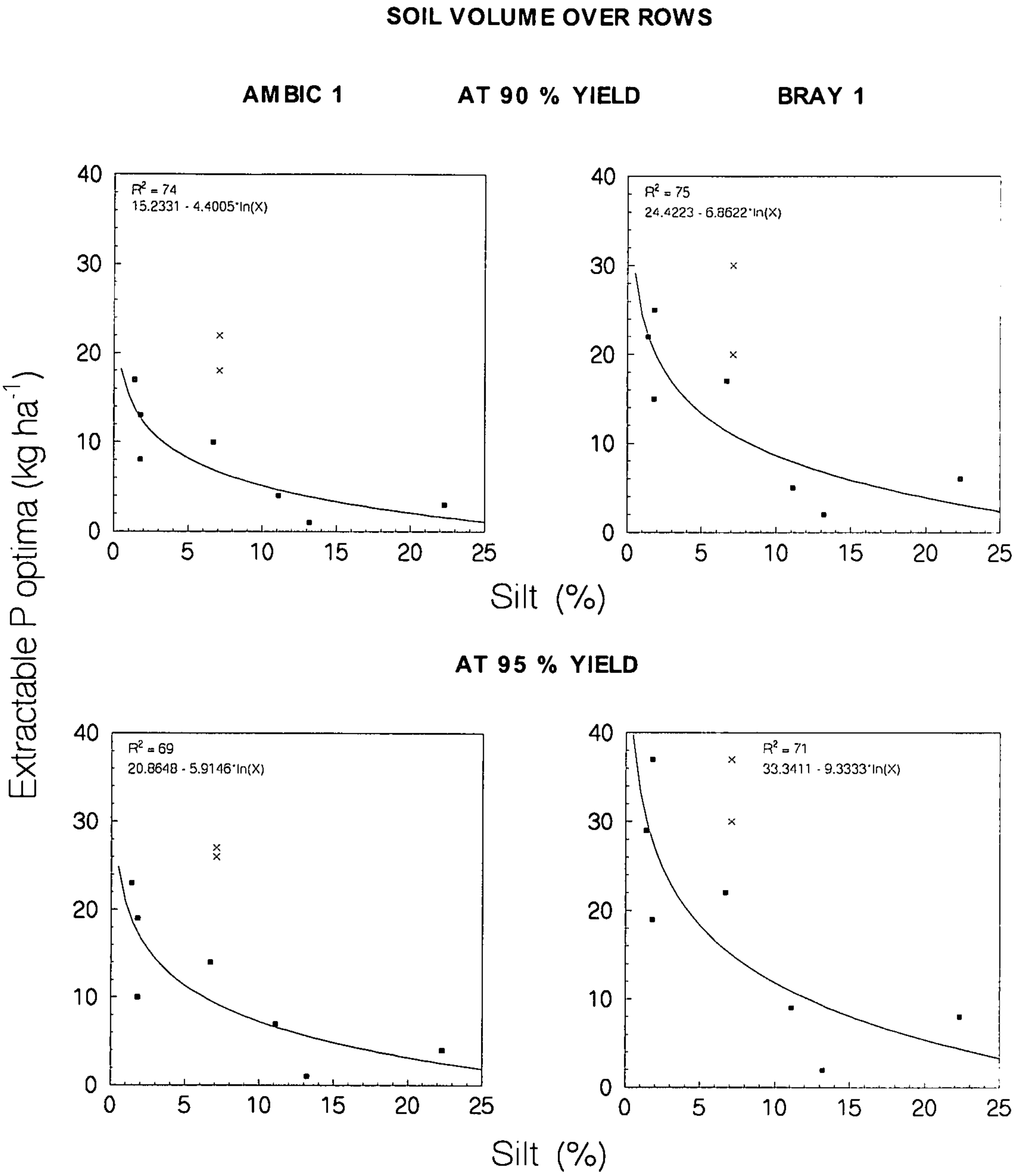

Figure 6.22 : Effects of silt content for a 300 mm wide strip over rows in the top 150 mm soil on extractable P (Ambic 1 or Bray 1) quantities required for 90 as well as 95 % relative yield. Data from Stilfontein (N x P) and Heidelberg (Lime x P) as indicated by a x-marker is excluded from relationships.

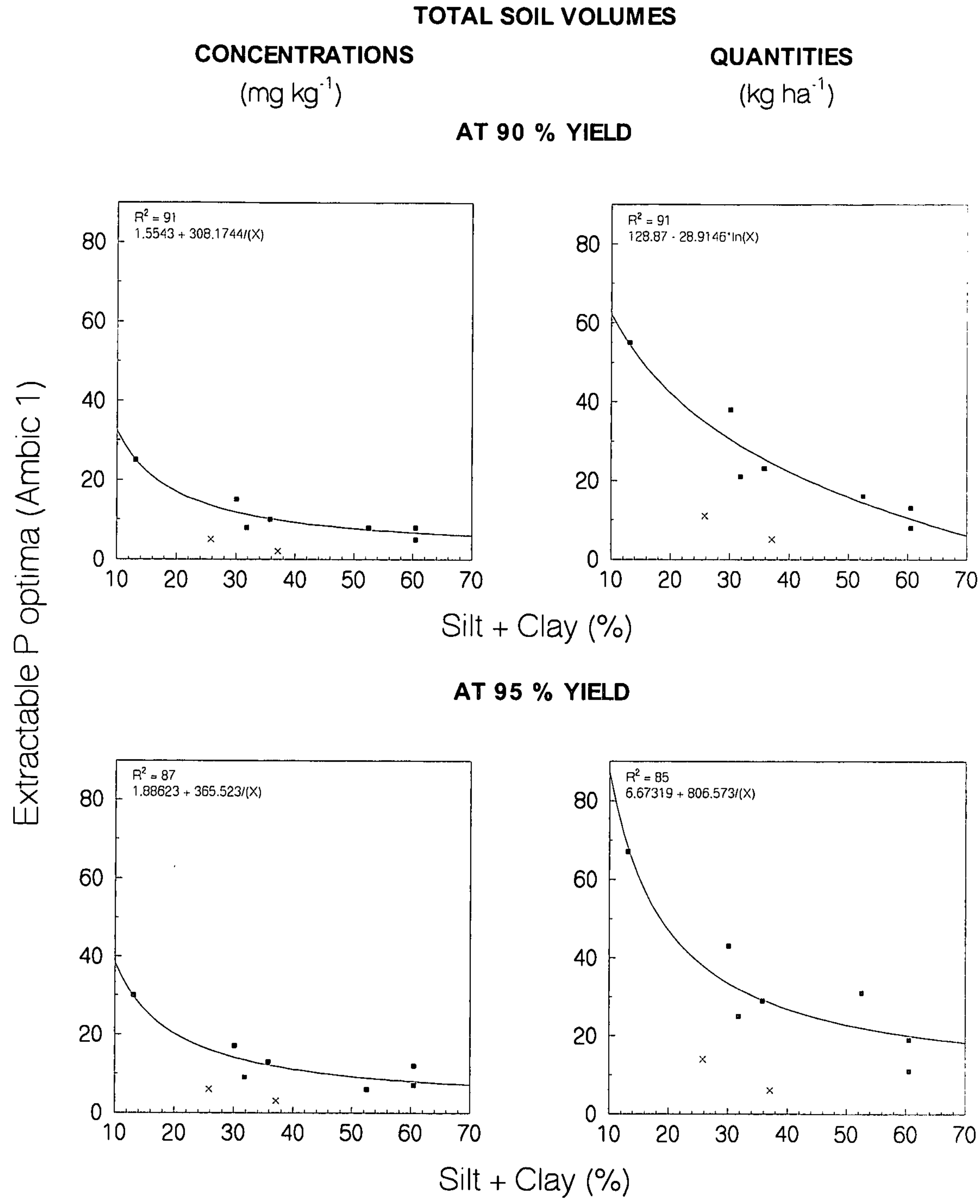

Figure 6.23 : Effects of silt-plus-clay content for total soil volumes in the top 150 mm soil on extractable P (Ambic 1) concentrations and quantities required for 90 as well as 95 % relative yield. Data from Ventersdorp and Lichtenburg trials as indicated by a x-marker is excluded from relationships.

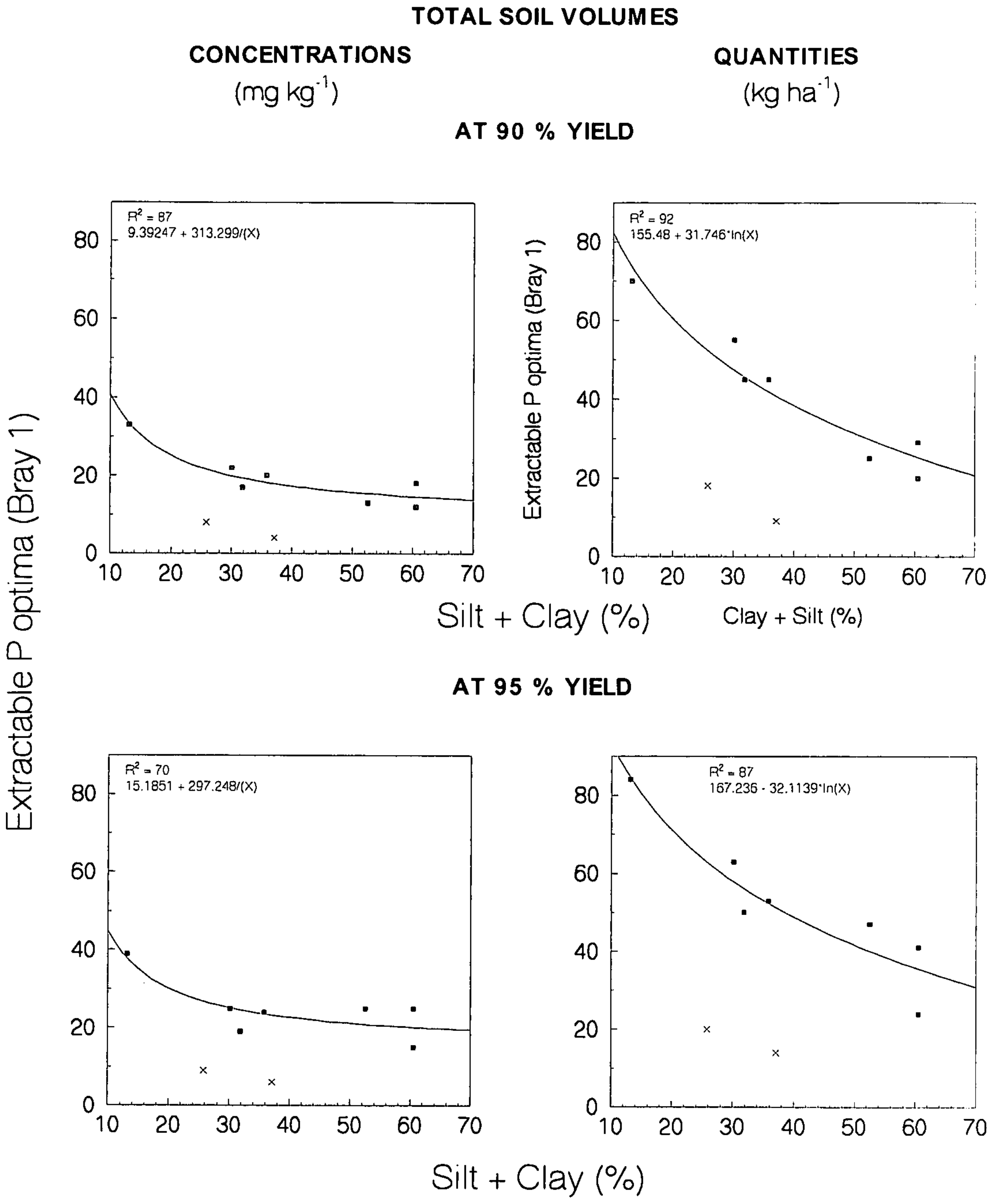

Figure 6.24 : Effects of silt-plus-clay content for total soil volumes in the top 150 mm soil on extractable P (Bray 1) concentrations and quantities required for 90 as well as 95 % relative yield. Data from Ventersdorp and Lichtenburg trials as indicated by a x-marker is excluded from relationships.

Table 6.5 : The concentration and quantity of extractable P (Ambic 1 and Bray 1) required in the total soil volume (150 mm deep) for either 90 or 95 % relative yield for various silt-plus-clay contents as derived from previously established relationships

Silt-plus-clay	Ambic 1		Bray 1		Silt-plus-clay	Ambic 1		Bray 1	
%	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	%	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}
	90 % relative yield					95 % relative yield			
13	25.3	54.7	33.5	74.1	13	30.0	68.7	38.1	84.9
14	23.6	52.6	31.8	71.7	14	28.0	64.3	36.4	82.5
15	22.1	50.6	30.3	69.5	15	26.3	60.4	35.0	80.3
16	20.8	48.7	29.0	67.5	16	24.7	57.1	33.8	78.2
17	19.7	46.9	27.8	65.5	17	23.4	54.1	32.7	76.3
18	18.7	45.3	26.8	63.7	18	22.2	51.5	31.7	74.4
19	17.8	43.7	25.9	62.0	19	21.1	49.1	30.8	72.7
20	17.0	42.2	25.1	60.4	20	20.2	47.0	30.0	71.0
21	16.2	40.8	24.3	58.8	21	19.3	45.1	29.3	69.5
22	15.6	39.5	23.6	57.4	22	18.5	43.3	28.7	68.0
23	15.0	38.2	23.0	55.9	23	17.8	41.7	28.1	66.5
24	14.4	37.0	22.4	54.6	24	17.1	40.3	27.6	65.2
25	13.9	35.8	21.9	53.3	25	16.5	38.9	27.1	63.9
26	13.4	34.7	21.4	52.0	26	15.9	37.7	26.6	62.6
27	13.0	33.6	21.0	50.9	27	15.4	36.5	26.2	61.4
28	12.6	32.5	20.6	49.7	28	14.9	35.5	25.8	60.2
29	12.2	31.5	20.2	48.6	29	14.5	34.5	25.4	59.1
30	11.8	30.5	19.8	47.5	30	14.1	33.6	25.1	58.0
31	11.5	29.6	19.5	46.5	31	13.7	32.7	24.8	57.0
32	11.2	28.7	19.2	45.5	32	13.3	31.9	24.5	55.9
33	10.9	27.8	18.9	44.5	33	13.0	31.1	24.2	54.9
34	10.6	26.9	18.6	43.5	34	12.6	30.4	23.9	54.0
35	10.4	26.1	18.3	42.6	35	12.3	29.7	23.7	53.1
36	10.1	25.3	18.1	41.7	36	12.0	29.1	23.4	52.2
37	9.9	24.5	17.9	40.8	37	11.8	28.5	23.2	51.3
38	9.7	23.7	17.6	40.0	38	11.5	27.9	23.0	50.4
39	9.5	22.9	17.4	39.2	39	11.3	27.4	22.8	49.6
40	9.3	22.2	17.2	38.4	40	11.0	26.8	22.6	48.8
41	9.1	21.5	17.0	37.6	41	10.8	26.3	22.4	48.0
42	8.9	20.8	16.9	36.8	42	10.6	25.9	22.3	47.2
43	8.7	20.1	16.7	36.1	43	10.4	25.4	22.1	46.4
44	8.6	19.5	16.5	35.3	44	10.2	25.0	21.9	45.7
45	8.4	18.8	16.4	34.6	45	10.0	24.6	21.8	45.0
46	8.3	18.2	16.2	33.9	46	9.8	24.2	21.6	44.3
47	8.1	17.5	16.1	33.3	47	9.7	23.8	21.5	43.6
48	8.0	16.9	15.9	32.6	48	9.5	23.5	21.4	42.9
49	7.8	16.3	15.8	31.9	49	9.3	23.1	21.3	42.3
50	7.7	15.8	15.7	31.3	50	9.2	22.8	21.1	41.6
51	7.6	15.2	15.5	30.7	51	9.1	22.5	21.0	41.0
52	7.5	14.6	15.4	30.0	52	8.9	22.2	20.9	40.3
53	7.4	14.1	15.3	29.4	53	8.8	21.9	20.8	39.7
54	7.3	13.5	15.2	28.8	54	8.7	21.6	20.7	39.1
55	7.2	13.0	15.1	28.3	55	8.5	21.3	20.6	38.5
56	7.1	12.5	15.0	27.7	56	8.4	21.1	20.5	38.0
57	7.0	12.0	14.9	27.1	57	8.3	20.8	20.4	37.4
58	6.9	11.5	14.8	26.6	58	8.2	20.6	20.3	36.8
59	6.8	11.0	14.7	26.0	59	8.1	20.3	20.2	36.3
60	6.7	10.5	14.6	25.5	60	8.0	20.1	20.1	35.8

6.4 Conclusion

The main objective of this study to determine the extractable P concentrations and quantities based on Ambic and Bray 1 extractions required in the soil volume over rows and in the total soil volume for either 90 or 95 % relative yields was obtained to a large extent. In fact, threshold extractable P values were derived for 10 out of the 14 localities that were included in this study. These threshold extractable P values were related to soil properties. Degree of leaching and silt-plus-clay content were the parameters that explained most of the variation. However, for reasons given it was decided to explore only the relationships between threshold extractable P values and silt-plus-clay contents over soils in more detail. By excluding data from two localities of which the topsoil contained lime, the R^2-values of the mentioned relationships improved substantially. Threshold extractable P values could be derived from a wide range of silt-plus-clay contents using these relationships. These threshold values can certainly be incorporated in phosphorus fertilization recommendations for maize provided that there is no lime in the soil. The obtained threshold values for lime containing soils can however also be implemented separately under similar conditions. It is suggested that not only the effect of silt-plus-clay content, but also the effect of the degree of leaching on extractable phosphorus warrants inclusion in future studies.

Threshold P values obtained in this study differed from those reported by Human & Van Biljon (1994) who suggested an optimum P soil test of 17 ± 2 mg kg^{-1} (Bray 1) at band placements of 5 to 11 kg P ha^{-1} for 95 % relative yield for all soils containing less than 35 % clay west of the Drakensberg mountains. The soil sampling method proposed by a task team that assisted the ARC-Grain Crops Institute in compiling these guidelines (LNR-Instituut Graangewasse, 1994) only suggested sampling between rows to a depth of 150 - 200 mm, since research results were based on this method. The sampling method in this study differed drastically from the traditional approach of sampling only between rows. In this study it was suggested that threshold P values required to obtain 90 % relative yield should rather be used than those for 95 % relative yield. However, P values required to obtain 95 % relative yield were also reported. Threshold P soil test values (Bray 1) required to obtain 90 or 95 % relative yield reported in this study were much higher on sandy soils and lower on clayey soils, i.e. at a silt-plus-clay content of 13 % 33.5 and 38.1 mg kg^{-1} for 90 and 95 % relative yield, respectively, but at a silt-plus-clay content of 60 % 14.6 and 20.1mg kg^{-1} for relative yields of 90 and 95 %, respectively.

Considering much higher extractable P (Bray 1) values to obtain 95 % relative yield reported in this study compared to that reported by Human & Van Biljon (1994), especially on sandy soils, it may be reasoned that much more P fertilizers will be sold for maize production also because most maize is being produced in the Free State and North West provinces (Crop Estimates Committee, 2001) on sandy soils containing less than 20 % clay. This expected impact may however not materialize, since the implementation of the soil sampling procedure in this study will measure P residues in enriched zones over maize rows which were previously excluded in soil sampling. Furthermore, the predominant practice in the larger maize producing areas with less than 20 % clay in the topsoil is or should be controlled traffic, fixed row systems (M.A. Prinsloo, ARC-Grain Crops Institute, Potchefstroom: Personal communication) under which P fertilizer is band placed at planting resulting in enriched zones over rows.

CHAPTER 7

SUMMARY AND APPLICATION OF RESEARCH RESULTS

As scientific information is increasingly required to guide the use of P to increase profit above input costs without producing undesirable impacts on the environment, the objective in studying soil fertility is to determine action that can be taken to improve nutrient use efficiency and make soils more productive. It is widely assumed that optimum or threshold extractable P requirement for maize is directly related to absolute yield. However, research done in KwaZulu-Natal by Farina et al. (1993) showed that the extractable P requirement is rather related to relative maize yield, irrespective of yield potential. Furthermore, they also reported that the optimum soil P values for different soils were related to the clay content. The rationale of this study was to use these criteria in obtaining P fertilization guidelines for the larger maize producing areas.

The overall objectives of this study were to establish :

- Relationships between Ambic 1 and Bray 1 extractable P and if possible to relate differences in these relationships to soil properties,
- Relationships between extractable soil P and fertilizer P application for the determination of P requirement factors (PRF's) based on Ambic 1 and Bray 1 extractions and if possible to relate differences in these PRF's to soil properties,
- Relationships between extractable soil P and maize yield to determine the extractable P concentrations and quantities based on Ambic 1 and Bray 1 extractions required to obtain either 90 or 95 % relative yield and if possible to relate soil P threshold values to soil properties over soils.

To accomplish these objectives 14 different fertilizer trials at various localities in the Free State, Gauteng, Mpumalanga and North West provinces have been established. For all trials different phosphorus treatments were applied in order to establish differences in extractable soil P levels which would result in different maize yields. Long-term average rainfall varied from 990 mm per annum for the Athole trial in the eastern maize producing region to 494 mm per annum for the Wolmaransstad trial in the western region. Durations of trials varied between one and nine seasons. Data sets from some trials were incomplete and in other cases unsuitable. Never the less enough useful data was available to meet all the set objectives.

The first objective of this study, namely to establish relationships between the P extracted by the Ambic 1 and Bray 1 methods firstly over soils, secondly in specific soils and thirdly to relate differences in these relationships for specific soils to soil properties, was met. Although simple regression equations with high R^2-values were obtained for relationships between Ambic 1 and Bray 1 extractions over soils, these equations may result in a very high degree of inaccuracy when used for P fertilizer recommendations. Relationships for different soils differ significantly from each other. Specific soil properties showed significant effects on the efficacy of the two extractants. Slopes of relationships between Ambic 1 and Bray 1 could be predicted by using exchangeable Ca in simple regression relationships (R^2-values between 80 and 83 %). Universal equations for the conversion of Ambic 1 to Bray 1 extractable P and *vice versa* should, at least include exchangeable Ca and possibly some other soil properties.

The second objective of this study to establish through linear regression analyses PRF's by relating extractable P concentrations and quantities as determined by either the Ambic 1 or Bray 1 extractants in soil volumes over rows and total soil volumes to P rates, was largely met. It was demonstrated that PRF's cannot be obtained over soils (R^2-values varied between 10 and 54 %), but certainly for each soil separately (R^2-values varied between 75 and 99 %). Large differences between the PRF's in total soil volumes (1.7 to 63.2 for Ambic 1 concentrations and 0.8 to 27.3 for Bray 1 quantities) indicated soils in this study differed in their behavior to applied P. This aspect should be accommodated in fertilizer recommendations. Furthermore, the attempt to relate the PRF's to soil properties by means of simple and multiple regression was successful. Simple regression equations with degree of leaching based on the clay content (R^2-values ranged between 60 and 78 %) were obtained. Also, multiple regression equations which contained either exchangeable Ca, Mg or K, silt content or degree of leaching based on the clay content were established (R^2-values ranged between 47 and 99 %). It is suggested that the simple regression equations with degree of leaching should be considered above the multiple regression equations for the determining of PRF's. This aspect warrants further research to test the validity thereof in more soils. However, some of the results reported can already be incorporated in phosphorus recommendation programs.

The final objective of this study, to determine the extractable P concentrations and quantities based on Ambic and Bray 1 extractions required in the soil volume over rows and in the total soil volume for either 90 or 95 % relative maize yields, was largely met. Threshold extractable P values were derived for 10 out of the 14 localities that were included in this study with varying R^2-values. These threshold extractable

P values were related to soil properties and it was found that the degree of leaching and silt-plus-clay content were the parameters that explain most of the variation. However, it was decided to explore only the relationships between threshold extractable P values and silt-plus-clay contents in more detail. By excluding data from two localities of which the topsoil contained lime, the R^2-values of the mentioned relationships improve substantially with the result that threshold extractable P values could be derived for the range of silt-plus-clay contents of the other eight localities. For example the threshold extractable soil P concentrations based on Bray 1 for the total soil volume to obtain 90 % relative yield varied from 33.5 mg kg^{-1} at 13 % silt-plus-clay to 14.6 mg kg^{-1} at 60 % silt-plus-clay. These derived P threshold values can be incorporated in phosphorus fertilization recommendations for maize when cultivated on soils that contain no traces of lime. Soil P threshold values that were established for soils containing lime can be applied to similar conditions. The effect of silt-plus-clay content together with the degree of leaching on soil extractable phosphorus extraction warrants further research.

As already stated, some of the above mentioned research results can be applied in phosphorus fertilizer recommendations. The approach should be to increase the extractable soil P to a specific threshold level, but if this level is reached it should only be maintained. The threshold P level for a soil is available from Table 6.5 provided the silt-plus-clay content is known, while the phosphorus requirement factor for a soil can be calculated from the equations in Table 5.5 provided the exchangeable Ca, Mg, K and Na contents as well as the clay content are known. However, if the extractable soil P level exceeds the threshold extractable soil P level then no additional P is recommended. If soil P is equal to the threshold, P removed by the crop should be applied the next season in order to maintain the soil P status. Equation 7.1 can be used for the determination of fertilizer P requirement. The application of above-mentioned approach can be explained by three case study examples with some of the required parameters given in Table 7.1.

$$FP = (TP - EP) \times PRF/YR \qquad \text{.......................................Equation 7.1}$$

Where parameters are only applicable to the total volume of the 0 - 150 mm soil layer :

FP = Fertilizer P requirement (kg ha^{-1})

TP = Threshold extractable P (mg kg^{-1} or kg ha^{-1} in either Ambic 1 or Bray 1)

EP = Extractable P present (mg kg^{-1} or kg ha^{-1} in either Ambic 1 or Bray 1)

PRF = Phosphorus requirement factor (either Ambic 1 or Bray 1)

YR = Number of years to raise extractable P to threshold level

Table 7.1 : Input parameters for the three case study examples

Parameters		**Soils**	
	A	**B**	**C**
Bray 1 extractable P (mg kg^{-1})	11	42	42
Exchangeable Ca (mg kg^{-1})	287	1800	380
Exchangeable Mg (mg kg^{-1})	80	320	62
Exchangeable K (mg kg^{-1})	60	550	72
Exchangeable Na (mg kg^{-1})	2	12	5
Clay (%)	11	28	30
Silt-plus-clay (%)	18	38	46
Build-up period (years)	1	1	1

Notice must be taken that only the concentration of extractable P (Bray 1) is known. By using the silt-plus-clay contents of the three soils the corresponding threshold extractable P values in total soil volumes as obtained from Table 6.5 are as follows : soil A = 26.8 mg kg^{-1}, soil B = 17.6 mg kg^{-1} and soil C = 16.2 mg kg^{-1}. Comparing the threshold extractable P values with the extractable P values in Table 7.1 it is shown that only soil A had a sub-threshold extractable P level. Thus, the PRF of only soil A is calculated by using the equation : PRF (Bray 1) = $(1.136 + 0.0551DL_c)^2$ = 5.1 (Table 5.5). With all the inputs for Equation 7.1 known (TP = 26.8 mg kg^{-1}, EP = 11 mg kg^{-1}, PRF = 5.1 and YR = 1) the fertilizer P requirement to raise the extractable P level to the threshold is then 80.6 kg ha^{-1}.

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Appendix 3.1 : Condensed detailed descriptions and properties of soils at localities according to the format suggested by the Pedology and Data Analysis Staff (1991)

Profile description

Profile No	: **Lichtenburg - N x P (Road side)**	Soil form	: Montagu
Land type map	: 2626 Wes-Rand	Soil family	: Baden
Latitude/Longitude	: 26°06'52" S/26°14'46" EO	Terrain unit	: 3
Land type No	: Bd10n	Slope	: 1.5%
Elevation	: 1447 m	Slope shape	: Straight
Climate zone	: 11S	Aspect	: North-west
Vegetation	: Agronomic cash crop (maize)	Water table	: None
Described by	: RW Bruce & CJJ Schmidt	Stoniness	: < 2% round and angular coarse gravel and stones
Date described	: 2001-07-09	Erosion	: None

Parent and underlying materials

Profile : Diamictite and shale (sedimentary and volcanic rocks) from the Dwyka Formation, Ecca Group, Karoo Sequence during the Carboniferous period (Keyser, 1986).

Land type : Border of (a) plinthic catena with upland duplex and margalitic soils rare and eutrophic red soils not widespread. Geology is made up by Ventersdorp and Dominion lava, where basement Complex granite occurs sporadically. Pans occupy 4 % of the land type. It occurs on A2 terrain units. Demarcated on map 2626 Wes-Rand and situated in climate zone 11S and (b) Glenrosa and/or Mispah forms (other soils may occur) with lime rare or absent in the entire landscape. Geology is made up by dolomite and chert belonging to the Chuniespoort Group, with chert gravels abundant on middle and foot slopes including valley bottoms. It occurs on A2 terrain units. Demarcated on map 2626 Wes-Rand and situated in climate zone 11S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-300	Moist; mechanical disturbed; moist dark brown 10YR3/3; sandy clay loam; fine sand; weak fine subangular blocky; slightly firm; slightly sticky to sticky; slightly plastic; few to common very fine and fine pores normal coating; fine cracks; strong effervescens; few clay cutans; very few gravel rock fragments, coarse gravel and stones; very few fine rounded biocasts; 1.5 seconds water absorption; few roots; gradual smooth transition.	Orthic
B	300-560	Moist; mechanical disturbed to undisturbed; moist brown 10YR4/3; sandy clay loam; fine sand; weak fine subangular blocky; slightly firm; slightly sticky to sticky; slightly plastic to plastic; few to common very fine and fine pores normal coating; fine cracks; strong effervescens; few to common clay cutans; very few fine rounded sesquioxide and lime concretions/nodules and biocasts; very few gravel rock fragments, coarse gravel and stones; 2 second water absorption; few roots; gradual wavy transition.	Neocarbonate
C	560-1300+	Moist; mechanical undisturbed; moist yellowish brown 10YR5/4; loam; fine sand; few to common fine distinct black and orange oxidized iron oxide, manganese/magnetite and white lime mottles; weak fine subangular blocky; slightly firm; slightly sticky to sticky; slightly plastic to plastic; few to common very fine to fine pores normal coating; strong effervescens; common clay and carbonate cutans; common to many gravel rock fragments, coarse gravel and stones; very few fine rounded biocasts; common to many fine rounded sesquioxides and lime concretions/nodules; 1.5 seconds water absorption; few roots.	Unspecified material with signs of wetness

Notes : Signs of wetness in C horizon is not widely seen and not prominent, thus not a good example. Land type according to coordinates is Bd10n, but according to properties of soil, it rather belongs to the close by Fa10c land type. Maybe the land type border was determined incorrectly.
Profile described within area of formerly trial area. At time of classification area was planted with maize by farmer.

Farmer : Wouter du Preez
Farm : Manana
Telephone : 018-632983

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Lichtenburg - N x P (Road side)

Lab no	Depth	Horizon	Texture fractions (%)							Electric
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	conductivity
	(mm)		<2µ	2-20µ	20-45µ	45-106µ	106-250µ	250-500µ	>500µ	($mS\ m^{-1}$)
4853	0-300	A	23.9	13.2	6.1	17.1	25.5	8.5	7.6	48.6
4854	300-560	B	24.0	17.3	6.8	26.5	17.1	5.4	4.6	58.2
4855	560-1300+	C	20.6	22.8	8.9	19.9	20.0	5.3	4.1	54.8

Lab no	Mineralogy *									CBD - method				Exchangeable
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn	CEC	acidity
	(%)												($cmol_c\ kg^{-1}$)	
4853	0	58	0	21	0	0	21	0	0	0.346	0.050	0.039	19.960	0.051
4854	5	9	4	56	0	0	26	0	0	0.434	0.060	0.035	19.991	0.049
4855	5	6	5	68	0	2	14	0	0	0.339	0.042	0.037	19.951	0.043

Lab no	$pH(H_2O)$	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			($mg\ kg^{-1}$)										(%)		
4853	8.05	7.36	0.60	0.01	57	3867	49	5	5.18	2	1	7	0.900	0.112	0.26
4854	8.09	7.40	0.33	0.01	49	3839	68	15	6.42	3	1	7	0.638	0.075	0.25
4855	8.16	7.48	0.32	0.01	43	3753	124	2	4.95	3	1	5	0.300	0.046	0.22

Bulk density ($kg\ m^{-3}$)

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	1328	1585	1551
15-30	1522	1573	1566
30-60	-	-	-

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Calculated from over row and between row volumes at 2.24 m row widths

Profile description

Profile No	**Lichtenburg - N x P (Veld side)**	Soil form	Montagu
Land type map	2626 Wes-Rand	Soil family	Baden
Latitude/Longitude	26°06′50″ S/26°14′45″ EO	Terrain unit	3
Land type No	Bd10n	Slope	1.5%
Elevation	1447 m	Slope shape	Straight
Climate zone	11S	Aspect	North-west
Vegetation	Agronomic cash crop (maize)	Water table	None
Described by	RW Bruce & CJJ Schmidt	Stoniness	< 2% round and angular coarse gravel and stones
Date described	2001-07-09	Erosion	None

Parent and underlying materials

Profile : Diamictite and shale (sedimentary and volcanic rocks) from the Dwyka Formation, Ecca Group, Karoo Sequence during the Carboniferous period (Keyser, 1986).

Land type : Border of (a) plinthic catena with upland duplex and margalitic soils rare and eutrophic red soils not widespread. Geology is made up by Ventersdorp and Dominion lava, where basement Complex granite occurs sporadically. Pans occupy 4 % of the land type. It occurs on A2 terrain units. Demarcated on map 2626 Wes-Rand and situated in climate zone 11S and (b) Glenrosa and/or Mispah forms (other soils may occur) with lime rare or absent in the entire landscape. Geology is made up by dolomite and chert belonging to the Chuniespoort Group, with chert gravels abundant on middle and foot slopes including valley bottoms. It occurs on A2 terrain units. Demarcated on map 2626 Wes-Rand and situated in climate zone 11S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-300	Moist; mechanical disturbed; moist dark brown 10YR3/2; sandy clay loam; fine sand; weak to moderate fine subangular blocky; slightly firm; slightly sticky to sticky; slightly plastic to plastic; few very fine and fine pores normal coating; fine cracks; strong effervescence; few clay cutans; very few gravel rock fragments, coarse gravel and stones; 2 seconds water absorption; few roots; clear smooth transition.	Orthic
B	300-500	Moist; mechanical disturbed to undisturbed; moist brown 10YR4/3; clay loam; fine sand; few fine faint yellow oxidized iron oxides; weak to moderate fine subangular blocky; slightly firm; slightly sticky to sticky; slightly plastic to plastic; few to common very fine and fine pores normal coating; fine cracks; strong effervescence; few to common clay cutans; few fine rounded sesquioxide and lime concretions/nodules; few gravel rock fragments, coarse gravel and stones; single 70 mm stone line in upper part of horizon; 2 seconds water absorption; few roots; gradual wavy transition.	Neocarbonate
C	500+	Moist; mechanical undisturbed; moist light olive brown 2.5Y5/3; loam; fine sand; few to common fine to medium distinct black and orange oxidized iron oxide and manganese/magnetite and white lime mottles; weak fine subangular blocky; slightly firm; slightly sticky to sticky; slightly plastic to plastic; few to common very fine to fine pores normal coating; strong effervescence; few to common clay and carbonate cutans; common to many gravel rock fragments, coarse gravel, stones and coarse stones; common to many fine rounded sesquioxides and lime concretions/nodules; 2 seconds water absorption; few roots.	Unspecified material with signs of wetness

Notes : Signs of wetness in C horizon is not widely seen and not prominent, thus not a good example. Land type according to coordinates is Bd10n, but according to properties of soil, it rather belongs to the close by Fa10c land type. Maybe the land type border was determined incorrectly.

Profile described within area of formerly trial area. At time of classification area was planted with maize by farmer.

Farmer : Wouter du Preez
Farm : Manana
Telephone : 018-6329833

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Lichtenburg - N x P (Veld side)

Lab no	Depth	Horizon	Texture fractions (%)							Electric conductivity
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	
	(mm)		<2µ	2-20µ	20-45µ	45-106µ	106-250µ	250-500µ	>500µ	(mS m^{-1})
4856	0-300	A	26.2	11.0	7.0	19.5	22.1	9.1	7.7	55.1
4857	300-500	B	30.2	19.2	7.5	13.9	13.7	6.1	10.3	59.5
4858	500+	C	15.1	29.6	18.9	21.4	7.9	3.7	3.0	52.6

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												(cmol$_c$ kg^{-1})	
4856	13	16	9	52	0	0	10	0	0	0.357	0.052	0.041	20.386	0.083
4857	5	10	5	66	0	2	12	0	0	0.495	0.070	0.047	20.254	0.062
4858	4	6	3	73	0	0	14	0	0	0.092	0.013	0.019	20.310	0.032

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4856	7.99	7.24	21.57	6.35	77	3883	84	1	8.96	2	1	8	1.035	0.105	0.41
4857	8.11	7.35	0.65	0.01	60	3777	140	1	5.32	3	1	5	0.667	0.081	0.31
4858	8.30	7.58	0.67	0.01	26	3746	179	2	6.40	3	1	5	0.180	0.029	0.16

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	1337	1657	1614
15-30	1499	1408	1420
30-60	-	-	-

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Calculated from over row and between row volumes at 2.24 m row widths

Appendix 3.1 continued

Profile description

Profile No	: **Wolmaransstad - N x P**	Soil form	: Bloemdal
Land type map	: 2726 Kroonstad	Soil family	: Roodeplaat
Latitude/Longitude	: 27°05'24" S/26°02'32" EO	Terrain unit	: 4
Land type No	: Bc19c	Slope	: 0.5%
Elevation	: 1377 m	Slope shape	: Concave
Climate zone	: 11S	Aspect	: North and south
Vegetation	: Agronomic cash crop (maize)	Water table	: None
Described by	: RW Bruce & CJJ Schmidt	Stoniness	: < 2% round and flat gravel and coarse gravel
Date described	: 2001-07-03	Erosion	: None

Parent and underlying materials

Profile : On border of alluvium from the Quaternary period and lava, chert and tuff (sedimentary and volcanic rocks) of the Rietgat Formation, Platberg Group and Ventersdorp Super Group during the Randium period (Schutte, 1986).

Land type : Plinthic catena with upland duplex and margalitic soils rare and eutrophic red soils widespread. Geology is made up by andesitic to basaltic lava of the Ventersdorp Supergroup with sporadic occurrence of Ventersdorp quartzite and grit. Demarcated on map 2627 Kroonstad and situated in climate zone 11S (Bruce & Schoeman, 1979b; Land Type Survey Staff, 1984).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-310	Dry; mechanical disturbed; dry red 2.5YR4/6; hard; moist dark reddish brown 2.5YR3/4; sandy loam; fine sand; apedal massive; friable; slightly sticky; slightly plastic; none to few very fine and fine pores normal coating; fine cracks; very few fine rounded sesquioxide concretions/nodules; very few gravel rock fragments and coarse gravel; 1 second water absorption; few roots; gradual smooth transition.	Orthic
B	310-840	Dry; mechanical undisturbed; dry red 2.5YR4/6; hard; moist dark reddish brown 2.5YR3/4; sandy loam; fine sand; common fine to medium faint brown unknown mottles; apedal massive; friable; slightly sticky; slightly plastic; common very fine and fine pores normal coating; fine cracks; few clay cutans; very few fine rounded sesquioxide concretions/nodules; few gravel rock fragments, coarse gravel and stones; 1 second water absorption; few roots; clear wavy transition.	Red apedal
C	840-1400+	Dry; mechanical undisturbed; slight discontinuous iron and manganese oxide nodular pan; single stone line 560 mm thick throughout the horizon; few roots.	Unspecified material with signs of wetness

Notes : Stone line contains hard plinthite some places, but is otherwise weakly cemented. It consists mainly of iron and manganese concretions/nodules with rounded alluvial quartz stones or otherwise amygdale (amandelsteen) related to Ventersdorp lava.

Profile described inside previous trial area. At time of classification planted with sunflower by farmer.

Farmer : Frans Marx
Farm : Uitval
Telephone : 083 254 1414 / 018 - 5962150

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Wolmaransstad N x P

Lab no	Depth	Horizon	Texture fractions (%)							Electric conductivity
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4848	0-310	A	13.5	22.3	4.2	27.0	2.8	7.8	23.4	9.6
4849	310-840	B	19.7	11.4	5.3	22.9	4.0	6.1	31.8	12.5

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												(cmol$_c$ kg^{-1})	
4848	21	69	0	0	0	3	0	0	0	0.821	0.056	0.026	2.549	0.047
4849	25	53	0	22	10	0	0	0	0	1.590	0.072	0.039	5.163	0.011

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4848	5.69	4.74	15.84	8.19	87	314	104	13	1.66	8	1	20	0.180	0.029	1.71
4849	6.12	5.13	1.25	0.12	35	567	271	1	3.50	3	2	14	0.225	0.035	0.21

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	-	-	1478
15-30	-	-	1697
30-60	-	-	1605

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Measured

Appendix 3.1 continued

Profile description

Profile No	**Koppies - N x P**	Soil form	Rensburg
Land type map	2726 Kroonstad	Soil family	Rietkuil
Latitude/Longitude	27°10'55" S/27°37'24" EO	Terrain unit	3 Upper
Land type No	Dc7a	Slope	1%
Elevation	1419 m	Slope shape	Convex
Climate zone	29S	Aspect	south
Vegetation	Agronomic cash crop (maize)	Water table	None
Described by	RW Bruce & CJJ Schmidt	Stoniness	None
Date described	2001-07-04	Erosion	None

Parent and underlying materials

Profile : Mudstone, siltstone and shale (sedimentary and volcanic rocks) from the Volksrust Formation, Ecca Group, Karoo Super Group during the Permian period (Schutte, 1986).

Land type : Prismacutanic and/or pedocutanic diagnostic horizons dominant. In addition, one of more of vertic, melanic and/or red structured diagnostic horizons may occur. Geology is made up Ecca shale and sandstone, with many dolerite sills. Sporadic occurrence of Basement Complex granite in the west. It occurs on A2 terrain units. Demarcated on map 2627 Kroonstad and situated in climate zone 29S (Bruce & Schoeman, 1979b; Land Type Survey Staff, 1984).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-500	Dry; mechanical disturbed to undisturbed; dry very dark grey 10YR3/1; very hard; moist black 2.5Y2/0; clay; fine sand; strong medium to coarse angular blocky; firm to very firm; sticky to very sticky; very plastic; few very fine and fine pores normal coating; fine, medium and coarse cracks; slight effervescence; many slickensides; many clay cutans; very few fine to medium rounded lime concretions/nodules; very few gravel rock fragments; 2 seconds water absorption; few roots; gradual wavy transition.	Vertic
G	500-950	Dry; mechanical undisturbed; dry light olive gray 5Y6/2; very hard; moist olive 5Y5/3; clay; fine sand; few fine faint orange oxidized iron oxide mottles; strong medium to coarse angular blocky; very firm; very sticky; very plastic; few very fine and fine pores normal coating; fine, medium and coarse cracks; moderate to strong effervescence; many slickensides; common to many clay cutans; few to common fine to medium rounded lime concretions/nodules; very few gravel rock fragments and coarse gravel; 6 seconds water absorption; few roots; diffuse wavy transition.	G horizon
C	950+	Dry to moist; mechanical undisturbed.	Saprolite

Notes : Although the soil profile was in a moist condition at the time of classification and description, some parameters of the A and G horizons could be described in the dry condition. Saprolite occurs as mudstone, rather than shale, with lime nodules. Saprolite is also gray with almost the same colour as the G horizon. Fragments of mudstone is found in the G horizon. Transition between G and C horizons is diffuse.

Profile described outside and adjacent to the trial area.

Farmer : Koppies black community - S'Bongile trust
Farm : Susannaskuil
Telephone :

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Koppies N x P

Lab no	Depth	Horizon	Texture fractions (%)							Electric
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	conductivity
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4846	0-500	A	58.7	1.8	6.9	8.7	13.4	3.0	9.9	109.7
4847	500-950	G	51.1	2.3	8.5	6.3	25.1	2.3	6.8	102.2

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												(cmol$_c$ kg^{-1})	
4846	7	43	14	29	7	0	0	0	0	0.264	0.082	0.047	27.782	0.027
4847	6	42	13	39	0	0	0	0	0	0.140	0.035	0.027	26.117	0.055

Lab no	pH(H$_2$O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4846	7.92	6.73	1.86	0.01	322	3907	797	195	16.0	2	2	7	0.795	0.082	0.10
4847	8.54	7.36	0.55	0.01	213	2582	1238	558	15.8	2	1	9	0.229	0.032	0.21

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	-	-	1084
15-30	-	-	1102
30-60	-	-	1136

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Measured

Profile description

Profile No	:	**Ventersdorp - N x P**	Soil form	:	Hutton
Land type map	:	2626 Wes-Rand	Soil family	:	Hayfield
Latitude/Longitude	:	26°06'22" S/26°47'04" EO	Terrain unit	:	4 Upper
Land type No	:	Fa15a	Slope	:	0.5%
Elevation	:	1494 m	Slope shape	:	Straight
Climate zone	:	18S	Aspect	:	Level
Vegetation	:	Agronomic cash crop (maize)	Water table	:	None
Described by	:	RW Bruce & CJJ Schmidt	Stoniness	:	< 2% flat coarse stones
Date described	:	2001-07-02	Erosion	:	None

Parent and underlying materials

Profile : Chert-rich dolomite, chert and remnants of chert (sedimentary and volcanic rocks) from the Eccles Formation, Malmani Sub Group, Chuniespoort Group, Transvaal Sequence during the Vaalian period (Keyser, 1986).

Land type : Dolomite and chert belonging to the Chuniespoort Group; chert and gravels are abundant on mid-slopes and foot slopes including valley bottoms (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-220	Dry; mechanical disturbed; dry yellowish red 5YR4/6; slightly hard; moist dark reddish brown 5YR3/4; sandy loam; fine sand; apedal massive; friable; non-sticky to sticky; non-plastic; few very fine and fine pores normal coating; fine cracks; very few fine to medium rounded sesquioxide concretions/nodules; very few coarse gravel; 1 second water absorption; few roots; gradual smooth transition.	Orthic
B1	220-450	Dry; mechanical undisturbed; dry red 2.5YR4/6; slightly hard; moist dark reddish brown 2.5YR3/4; sandy loam; fine sand; apedal massive; friable; slightly sticky; slightly plastic; few very fine and fine pores normal coating; fine cracks; very few fine to medium rounded sesquioxide concretions/nodules; very few coarse gravel; 1 second water absorption; few roots; clear to gradual smooth to wavy transition.	Red apedal
B2	450-1500+	Dry; sandy clay loam; fine sand; mechanical undisturbed; moderate discontinuous nodular pan of iron and manganese oxides; very many fine, medium and coarse rounded sesquioxide concretions/nodules; single 50 mm stone line in upper part of horizon; 1 second water absorption; few roots.	Hard plinthic

Notes : Hard plinthic B is not continuous. It is not a very good example of hard plinthite, but cannot be dug by a spade. It becomes harder with increasing depth (>1200 mm) as well as more cemented. However, root development in the plinthic horizon is good. The white coarse gravel in the A and B horizons is white vein quarts. The stone line in the hard plinthite is not clear, but consists of some big fragments.

Profile described outside on border of trial area.

Farmer : Magopa Trust
Farm : Magopa
Telephone : 014-5439387

Appendix 3.1 continued

Chemical, physical and mineralogical information from profile pit

Locality : Ventersdorp - N x P

Lab no	Depth	Horizon	Texture fractions (%)							Electric conductivity
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4840	0-220	A	14.7	11.1	5.3	32.9	3.5	19.0	13.8	6.0
4841	220-450	B1	18.2	8.4	7.0	29.9	4.2	10.6	22.1	10.2
4842	450-1500+	B2	21.3	12.6	7.5	23.8	5.9	8.9	21.7	3.1

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												(cmol$_c$ kg^{-1})	
4840	42	28	7	5	0	11	0	7	0	2.420	0.139	0.087	1.310	0.852
4841	51	24	12	0	0	8	0	5	0	2.480	0.126	0.075	1.497	0.055
4842	10	76	0	0	0	9	0	5	0	3.210	0.106	0.086	1.191	0.274

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4840	4.39	3.90	7.32	4.37	40	38	10	20	0.81	31	2	73	0.322	0.043	65.02
4841	5.28	4.74	1.00	0.26	33	191	48	1	0.59	8	1	43	0.255	0.041	3.67
4842	4.77	4.44	0.94	0.42	10	46	80	1	1.79	5	1	23	0.143	0.031	23.01

Bulk density (kg m^{-3})				Texture (%)		
Depth (mm)	Over rows	Between rows	Over plus between rows***	Clay	Silt	Sand
0-150	1495	1530	1525	14.3	8.3	77.8
150-300	1620	1678	1670	14.8	8.7	77.0
300-600	1563	1530	1534	16.7	10.3	72.9

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Calculated from over row and between row volumes at 2.24 m row widths as practised in area

Chemical information from treatment plots[1]

Statistical criteria	pH(KCl)	K	Ca	Mg	Na	Acid saturation	Exchangeable acidity	CEC
		(mg kg^{-1})				(%)	(cmol$_c$ kg^{-1})	
Average	5.40	48	227	69	2	0.06	1.89	4.28
Median	5.40	47	223	70	1	0.04	1.84	1.95
Minimum	4.25	29	54	10	1	0.02	0.94	0.8
Maximum	6.30	74	363	100	23	0.49	2.75	57.5

[1] - Information obtained from the 0-150 mm topsoil samples collected from treatment plots after side-dressing, i.e. six weeks after planting, during the 2001/02 growing season

Appendix 3.1 continued

Profile description

Profile No	:	**Viljoenskroon - N x P**	Soil form	:	Bloemdal
Land type map	:	2726 Kroonstad	Soil family	:	Waldo
Latitude/Longitude	:	27°12'10" S/26°58'20" EO	Terrain unit	:	3 Upper
Land type No	:	Bd14a	Slope	:	1%
Elevation	:	1334 m	Slope shape	:	Convex to straight
Climate zone	:	31S	Aspect	:	South-east
Vegetation	:	Agronomic cash crop (maize)	Water table	:	1700 mm
Described by	:	RW Bruce & CJJ Schmidt	Stoniness	:	None
Date described	:	2001-07-10	Erosion	:	Slight wind erosion

Parent and underlying materials

Profile : Aeolian sand during the Quaternary period (Schutte, 1986).

Land type : Plinthic catena with upland duplex and margalitic soils rare and eutrophic rd soils are not spread. Geology is made up by Ecca sandstone, mudstone and shale, with occasional dolerite sills and with sporadic occurrence of Hekpoort lava, diabase and quartzite in east. Aeolian sand overlies nearly all rocks. Pans occupy 1 % of land type. It occurs on A2 terrain units. Demarcated on map 2726 Kroonstad and situated in climate zone 31S (Bruce & Schoeman, 1979b; Land Type Survey Staff, 1984).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-380	Moist; mechanical disturbed; moist brown 7.5YR4/4; loamy sand; fine sand; few fine faint orange oxidized iron oxide mottles; apedal massive; friable; slightly sticky; slightly plastic; none to few very fine and fine pores normal coating; 1 second water absorption; few to common roots; gradual tonguing transition.	Orthic
B1	380-720	Moist; mechanical disturbed to undisturbed; moist yellowish red 5YR4/6; sandy loam; fine sand; few fine faint orange oxidized iron oxide mottles; apedal massive; friable to slightly firm; slightly sticky; slightly plastic; few very fine and fine pores normal coating; few clay cutans; 1 second water absorption; few to common roots; gradual wavy transition.	Red apedal
B2	720-1170	Moist; mechanical undisturbed; moist yellowish red 5YR4/6; sandy loam; fine sand; many fine to medium faint orange, red and yellow oxidized iron oxide mottles; apedal massive; slightly firm; slightly sticky; slightly plastic; few very fine to fine pores normal coating; few to common clay cutans; very few fine rounded sesquioxide concretions/nodules; 1 second water absorption; few to common roots; abrupt wavy transition.	Red apedal
B3	1170-1500+	Moist; mechanical undisturbed; moist light yellowish brown 10YR6/4; moderate to strong continuous iron and manganese nodular pan; few to common clay cutans; many to very many fine, medium and coarse rounded sesquioxide concretions/nodules; few roots.	Hard plinthic

Notes : B horizon appears to be yellow but measures red according to the Munsell in the moist condition, thus qualifying as red. B3 horizon is hard plinthic, strongly gleyed. Because of wavy soil layers or horizons, soil depth also varies and thus more than one soil may be found within the borders of the trial area and surroundings.

Profile described outside on border of trial area.

Farmer : Pieter Roux
Farm : Northleigh
Telephone :

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Viljoenskroon N x P

Lab no	Depth	Horizon	Texture fractions (%)							Electric conductivity
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4870	0-380	A	11.7	1.4	3.0	25.1	43.3	14.0	2.6	4.5
4871	380-720	B1	18.7	2.0	2.8	24.7	42.1	8.7	2.0	5.8
4872	720-1170	B2	17.1	1.9	2.8	24.5	42.0	9.6	2.7	8.6

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												($cmol_c$ kg^{-1})	
4870	28	56	8	0	0	8	0	0	0	0.626	0.068	0.008	1.584	0.095
4871	57	23	6	0	0	8	0	6	0	0.961	0.102	0.004	2.284	0.048
4872	63	20	9	0	0	8	0	0	0	0.909	0.101	0.005	2.172	0.017

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4870	5.15	4.35	11.61	6.26	47	196	47	1	2.25	5	1	65	0.154	0.024	5.97
4871	5.39	4.78	0.94	0.01	22	322	69	1	1.61	2	1	41	0.180	0.028	2.10
4872	5.68	5.02	0.78	0.01	19	243	108	1	1.43	2	1	27	0.143	0.025	0.78

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	1474	1414	1426
15-30	1733	1536	1575
30-60	1516	1489	1494

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Calculated from over row and between row volumes at 1.5 m row widths

Appendix 3.1 continued

Profile description

Profile No	: **Stilfontein - N x P / P source**	Soil form	: Bloemdal
Land type map	: 2626 Wes-Rand	Soil family	: Waldo
Latitude/Longitude	: 26°43'34" S/26°48'05" EO	Terrain unit	: 3
Land type No	: Ba42b	Slope	: 0.5%
Elevation	: 1357 m	Slope shape	: Straight
Climate zone	: 21S	Aspect	: South-west
Vegetation	: Agronomic cash crop (maize)	Water table	: None
Described by	: RW Bruce & CJJ Schmidt	Stoniness	: None
Date described	: 2001-07-03	Erosion	: None

Parent and underlying materials

Profile :	Soil cover (sedimentary and volcanic rocks) during the Quaternary Tertiary period (Keyser, 1986).
Land type :	Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils are widespread. Geology is made up by Witwatersrand quartzite and shale with Ventersdorp lava and Basement Complex granite in places. It occurs on A3 terrain units. Demarcated on map 2626 West Rand and situated in climate zone 21S (Bruce & Schoeman, 1979a; Land Type Survey Staff, 1984).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-350	Dry; mechanical disturbed; dry dark red 2.5YR3/6; hard; moist dark reddish brown 2.5YR3/4; sandy clay loam; fine sand; apedal massive; friable; slightly sticky; slightly plastic; few very fine and fine pores normal coating; fine cracks; 1 second water absorption; none to few roots; gradual smooth transition.	Orthic
B1	350-760	Dry; mechanical undisturbed; dry red 2.5YR4/6; slightly hard to hard; moist dark red 2.5YR3/6; sandy clay loam; fine sand; apedal massive; friable; slightly sticky; slightly plastic; few very fine and fine pores normal coating; fine cracks; few clay and red sesquioxide cutans; very few fine to medium rounded sesquioxide concretions/nodules; very few gravel rock fragments; 1 second water absorption; none to few roots; diffuse smooth transition.	Red apedal
B2	760-1460	Dry; mechanical undisturbed; dry red 2.5YR4/6; slightly hard to hard; moist dark red 2.5YR3/6; sandy clay loam; fine sand; few fine to medium faint reddish brown oxidized iron oxide mottles; apedal massive; friable; slightly sticky; slightly plastic; few very fine and fine pores normal coating; fine cracks; few clay and red sesquioxide cutans; very few fine to medium rounded sesquioxide concretions/nodules; very few gravel rock fragments; 1 second water absorption; none to few roots; clear wavy transition.	Red apedal
C	1460+	Dry; mechanical undisturbed; moderate to strong discontinuous iron and manganese oxide nodular pan.	Unspecified material with signs of wetness

Notes : B horizon divided as B1 and B2 on basis of slightly (very faint) colour difference, as the difference cannot be reflected/measured by the Munsell chart. Signs of wetness is few within hard plinthic layer (C).

Profile described inside previous trial area. At the time of classification the soil was barren and not planted by farmer.

Farmer : Gideon Martinson
Farm : Buffeldoorns
Telephone : 018-4844632

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Stilfontein - N x P / P-source

Lab no	Depth	Horizon	Texture fractions (%)							Electric conductivity
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4850	0-350	A	23.0	7.1	6.1	16.9	5.9	16.1	24.7	13.1
4851	350-760	B1	29.4	6.9	6.9	18.4	6.5	12.4	21.2	14.2
4852	760-1460	B2	32.1	7.0	7.4	15.7	6.3	11.8	21.5	25.0

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												(cmol$_c$ kg^{-1})	
4850	52	25	13	5	0	0	0	5	0	2.810	0.110	0.064	3.321	0.038
4851	54	22	9	5	0	0	0	10	0	2.680	0.115	0.048	3.322	0.011
4852	22	72	0	0	0	0	0	6	0	2.750	0.110	0.044	4.296	0.008

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4850	5.39	4.59	2.35	0.63	179	427	83	1	2.11	23	5	22	0.589	0.062	1.13
4851	5.89	5.21	0.57	0.01	52	430	106	36	0.97	6	3	17	0.338	0.042	0.33
4852	6.33	5.60	0.64	0.01	26	470	227	1	1.31	4	3	11	0.203	0.035	0.19

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	-	-	1688
15-30	-	-	1547
30-60	-	-	1459

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Measured

Appendix 3.1 continued

Profile description

Profile No	: **Heidelberg - N x P**	Soil form	: Avalon
Land type map	: 2628 East Rand	Soil family	: Vryheid
Latitude/Longitude	: 26°42′12″ S/28°18′27″ EO	Terrain unit	: 3 Lower
Land type No	: Ba30	Slope	: 2.5%
Elevation	: 1607 m	Slope shape	: Convex
Climate zone	: 21S	Aspect	: East
Vegetation	: Agronomic cash crop (maize)	Water table	: None
Described by	: RW Bruce & CJJ Schmidt	Stoniness	: None
Date described	: 2001-06-25	Erosion	: Slight sheet water partially stabilized

Parent and underlying materials

Profile :	Sandstone, shale and coal beds (sedimentary and volcanic rocks) of the Vryheid Formation and Ecca Group of the Karoo Sequence during the Permian period (Keyser, Botha & Groenewald, 1986).
Land type :	Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils are widespread. Geology is made up by andesitic lava of the Hekpoort Formation of the Pretoria Group - Transvaal Sequence and dolerite, sandstone, grit and shale of the Ecca Group - Karoo Sequence. It occurs on A3 terrain units. Demarcated on map 2628 East Rand and situated in climate zone 21S (Schoeman & Fitzpatrick, 1985a; Land Type Survey Staff, 1985).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-470	Dry; mechanical disturbed; dry brown 7.5YR4/4; apedal massive; hard; moist dark brown 7.5YR3/2; sandy clay loam; medium sand; friable to slightly firm; slightly sticky; slightly plastic; few very fine and fine pores normal coating; fine cracks; 1 second water absorption; few roots; gradual smooth transition.	Orthic
B1	470-1050	Moist; mechanical undisturbed; moist strong brown 7.5YR4/6; sandy clay loam; fine sand; few medium faint yellow and brown oxidized iron oxide mottles; apedal massive; slightly firm; slightly sticky; slightly plastic; common very fine and fine pores normal coating; few clay cutans; very few rounded medium sesquioxide concretions/nodules; 1 second water absorption; few roots; gradual smooth transition.	Yellow-brown apedal
B2	1050+	Moist; mechanical undisturbed; moist yellowish brown 10YR5/4; sandy clay; fine sand; many coarse prominent red and black oxidized iron oxide mottles; apedal massive; slightly firm; slightly sticky; slightly plastic; common very fine and fine pores normal coating; few clay cutans ; very few rounded medium sesquioxide concretions/nodules; 1 second water absorption; few roots; gradual smooth transition.	Soft plinthic

Notes	:	Profile described outside on border of previous trial area. At time of classification planted with maize by farmer.

Farmer	:	Morris Leonard
Farm	:	Wolwepan
Telephone	:	083 447 2288 / 016-3721432

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Heidelberg - N x P

Lab no	Depth	Horizon	Texture fractions (%)							Electric conductivity
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4816	0-470	A	25.1	6.7	5.4	22.2	4.9	20.4	16.7	16.9
4817	470-1050	B1	34.3	3.9	6.0	18.0	6.0	13.1	18.9	20.7
4818	1050+	B2	36.4	5.8	7.3	16.4	6.6	12.8	16.7	22.2

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												(cmol$_c$ kg^{-1})	
4816	13	77	0	0	0	10	0	0	0	0.989	0.140	0.018	3.312	0.082
4817	27	31	8	34	0	0	0	0	0	1.650	0.137	0.009	3.760	0.014
4818	68	32	0	0	0	0	0	0	0	2.010	0.141	0.006	3.850	0.018

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4816	5.25	4.47	1.67	0.60	71	451	90	12	3.04	12	1	56	0.510	0.050	2.48
4817	6.23	5.47	0.86	0.01	25	346	236	3	2.79	4	1	19	0.202	0.036	0.37
4818	5.99	5.30	0.50	0.01	29	262	295	6	5.04	2	1	17	0.128	0.027	0.47

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	1747	1755	1753
15-30	1685	1747	1735
30-60	1448	1472	1467

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Calculated from over row and between row volumes at 1.5 m row widths as practised in area

Appendix 3.1 continued

Profile description

Profile No	: **Heidelberg - Lime x P**	Soil form	: Hutton
Land type map	: 2628 East Rand	Soil family	: Suurbekom
Latitude/Longitude	: 26°42'12" S/28°18'27" EO	Terrain unit	: 1
Land type No	: Ba30	Slope	: 1%
Elevation	: 1607 m	Slope shape	: Convex
Climate zone	: 21S	Aspect	: East
Vegetation	: Agronomic cash crop (maize)	Water table	: None
Described by	: RW Bruce & CJJ Schmidt	Stoniness	: None
Date described	: 2001-06-25	Erosion	: None

Parent and underlying materials

Profile : Sandstone, shale and coal beds (sedimentary and volcanic rocks) of the Vryheid Formation and Ecca Group of the Karoo Sequence during the Permian period (Keyser, Botha & Groenewald, 1986).

Land type : Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils are widespread. Geology is made up by andesitic lava of the Hekpoort Formation of the Pretoria Group - Transvaal Sequence and dolerite, sandstone, grit and shale of the Ecca Group - Karoo Sequence. It occurs on A3 terrain units. Demarcated on map 2628 East Rand and situated in climate zone 21S (Schoeman & Fitzpatrick, 1985a; Land Type Survey Staff, 1985).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-500	Dry; mechanical disturbed; dry dark reddish brown 2.5YR3/4; weak fine subangular blocky; hard; moist dark reddish brown 2.5YR2/4; sandy loam; fine sand; slightly firm; slightly sticky; slightly plastic; few very fine and fine pores normal coating; fine cracks; few clay and organic cutans; very few fine round biocasts; 2 seconds water absorption; common roots; gradual smooth transition.	Orthic
B1	500-1030	Dry; mechanical undisturbed; dry dark reddish brown 2.5YR3/6;weak fine subangular blocky; hard; moist dusky red 10R3/4; sandy clay loam; fine sand; slightly firm; slightly sticky; slightly plastic; few very fine and fine pores normal coating; fine cracks; very few fine round biocasts; 2 seconds water absorption; few roots; gradual smooth transition.	Red apedal
B2	1030+	Dry; mechanical undisturbed; dry red 10R4/6;apedal massive; slightly hard; moist dusky red 10R3/4; sandy clay loam; fine sand; slightly firm; slightly sticky; slightly plastic; few very fine and fine pores normal coating; fine cracks; 2 seconds water absorption; few roots; gradual smooth transition.	Red apedal

Notes : Profile described outside on border of previous trial area. At time of classification planted with maize by farmer.

Farmer : Morris Leonard
Farm : Wolwepan
Telephone : 083 447 2288 / 016-3721432

Chemical, physical and mineralogical information

Locality : Heidelberg - Lime x P

Lab no	Depth	Horizon	Texture fractions (%)							Electric
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	conductivity
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4819	0-500	A	16.2	7.1	4.7	28.8	3.4	20.7	18.5	27.2
4820	500-1030	B1	22.8	4.7	4.4	25.1	9.2	14.5	18.6	54.7
4821	1030+	B2	34.2	5.3	5.5	20.4	5.3	12.1	17.9	32.4

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn	CEC	acidity
	(%)												(cmol$_c$ kg^{-1})	
4819	21	73	0	0	0	0	0	6	0	1.670	0.073	0.028	2.695	0.068
4820	24	67	0	0	0	0	0	9	0	2.830	0.130	0.021	4.570	0.025
4821	36	53	0	0	0	0	0	11	0	2.900	0.093	0.030	6.008	0.016

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4819	5.42	5.26	18.47	8.98	118	283	110	1	2.71	24	4	43	0.435	0.049	2.52
4820	5.62	4.95	1.56	0.05	29	598	173	13	1.58	7	5	23	0.465	0.051	0.54
4821	5.94	5.15	1.00	0.01	31	594	349	17	1.79	7	5	17	0.232	0.032	0.27

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	1331	1362	1356
15-30	1542	1619	1604
30-60	1596	1617	1613

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Calculated from over row and between row volumes at 1.5 m row widths as practised in area

Appendix 3.1 continued

Profile description

Profile No	: **Athole - P source**	Soil form	: Hutton
Land type map	: 2630 Mbabane	Soil family	: Lillieburn
Latitude/Longitude	: 26°35′33″ S/30°29′51″ EO	Terrain unit	: 3
Land type No	: Ac36a	Slope	: 1%
Elevation	: 1620 m	Slope shape	: Convex
Climate zone	: 110 S	Aspect	: East
Vegetation	: Agronomic cash crop (maize)	Water table	: None
Described by	: RW Bruce & CJJ Schmidt	Stoniness	: None
Date described	: 2001-0	Erosion	: Slight sheet water erosion, partially stabilized

Parent and underlying materials

Profile : Grit, sandstone, shale and coalseam (sedimentary and volcanic rocks) of the Vryheid Formation and Ecca Group of the Karoo Sequence during the Permian period (Walraven, 1984).

Land type : Red-yellow apedal, freely drained soils with red and yellow dystrophic and /or mesotrophic soils. Geology is made up by gabbro and ultrabasic rocks of the Usushwana Complex, shale and sandstone of the Ecca Group - Karoo Sequence and lava, pyroclasts, quartzite and schist if the Insuze Group - Pongola Sequence. It occurs on B4 terrain units. Demarcated on map 2630 Mbabane and situated in climate zone 110S (Schoeman & Fitzpatrick, 1985b; Land Type Survey Staff, 1985).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-300	Dry; mechanical disturbed; dry yellowish brown 10YR5/4; apedal massive; hard; moist brown 10YR4/3; clay loam; fine sand; slightly firm to firm; sticky; plastic; none to few very fine and fine pores normal coating; fine cracks; very few fine rounded sesquioxide concretions/nodules; very few gravel; 2 seconds water absorption; few roots; gradual smooth transition.	Orthic
B1	300-570	Dry; mechanical undisturbed; dry yellowish red 5YR5/8;apedal massive; slightly hard; moist yellowish red 5YR4/8; clay; fine sand; friable; sticky; plastic; few very fine and fine pores normal coating; fine cracks; few clay cutans; common fine rounded sesquioxide concretions/nodules; common gravel rock fragments; single stone line 50 mm thick in upper part of horizon; 1 second water absorption; few roots; gradual wavy transition	Red apedal
C	570+	1 second water absorption.	Unspecified material

Notes : The Orthic A horizon is situated on a "yellowish" red-brown apedal B with a prominent stone line. B horizon is very thin and is situated on highly weathered shale parent material. The parent material © horizon) has definite lithocutanic properties with many roots, indicating a high agronomic value/use. The colour of the upper part of the B horizon appears more yellow than red, while the lower part is the opposite, thus appearing to be a border between Hutton and Clovelly.

Profile described outside on border of trial area.

Farmer : Research farm - Manager SD Niemann
Farm : Athol
Telephone : 083 701 5425

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Athole - P source

Lab no	Depth (mm)	Horizon	Texture fractions (%) Clay $<2\mu$	Silt $2\text{-}20\mu$	Coarse silt $20\text{-}45\mu$	very fine sand $45\text{-}106\mu$	fine sand $106\text{-}250\mu$	medium sand $250\text{-}500\mu$	coarse sand $>500\mu$	Electric conductivity ($mS\ m^{-1}$)
4832	0-300	A	39.3	8.0	7.2	13.9	11.5	7.9	11.0	7.8
4833	300-570	B1	44.2	7.7	6.9	13.4	12.6	5.6	9.7	5.6
4834	570+	C	29.5	2.2	10.7	8.1	35.2	3.0	13.1	4.2

Lab no	Mineralogy * Kt (%)	Qz (%)	Mi (%)	St (%)	Is (%)	Go (%)	Ct (%)	Hm (%)	Gb (%)	CBD - method Fe (%)	Al (%)	Mn (%)	CEC ($cmol_c\ kg^{-1}$)	Exchangeable acidity ($cmol_c\ kg^{-1}$)
4832	27	39	0	6	0	17	0	0	11	4.600	1.571	0.004	2.194	0.817
4833	39	37	0	6	0	10	0	0	8	4.280	1.218	0.003	1.608	0.102
4834	67	12	4	0	0	13	0	0	4	4.130	0.471	0.016	1.070	0.251

Lab no	$pH(H_2O)$	pH(KCl)	Exchangeable cations ($mg\ kg^{-1}$) Bray I P	Ambic I P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe	Org C** (%)	Tot N (%)	AS (%)
4832	4.74	4.28	3.13	1.61	38	181	45	1	2.74	5	4	137	1.733	0.122	37.24
4833	5.16	4.84	0.71	0.11	4	179	72	1	2.34	1	3	111	0.952	0.061	6.34
4834	4.90	4.75	0.50	0.01	7	101	29	14	4.12	6	1	22	0.180	0.022	23.45

Bulk density ($kg\ m^{-3}$)

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	1216	1325	1289
15-30	1167	1251	1223
30-60	1087	1120	1109

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Calculated from over row and between row volumes at 0.9 m row widths as practised in area

Appendix 3.1 continued

Profile description

Profile No	:	**Belfast - P source**	Soil form	:	Avalon
Land type map	:	2528 Pretoria	Soil family	:	Avondale
Latitude/Longitude	:	25°45'56" S/29°59'03" EO	Terrain unit	:	1
Land type No	:	Ad1a	Slope	:	1%
Elevation	:	1970 m	Slope shape	:	Convex
Climate zone	:	50S	Aspect	:	South
Vegetation	:	Agronomic cash crop (maize)	Water table	:	None
Described by	:	RW Bruce & CJJ Schmidt	Stoniness	:	None
Date described	:	2001-06-26	Erosion	:	Slight wind

Parent and underlying materials

Profile :	Shale, shaly sandstone, grit, sandstone, conglomerate and coal in places near base and top (sedimentary and volcanic rocks) of the Ecca Formation, Karoo Sequence during the Permian period (Walraven, 1978).
Land type :	Red-yellow apedal, freely drained soils which may be yellow and distrophic and/or mesotrophic. Geology is made up by shale, sandstone and grit of the Ecca Group, Karoo Sequence. It occurs on A3 terrain units. Demarcated on map 2528 Pretoria and situated in climate zone 50S (Schoeman , Meldahl-Johnsen, Fitzpatrick & Verster, 1985; Land Type Survey Staff, 1987).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-400	Dry; mechanical disturbed; dry brown 10YR4/3; apedal massive; slightly hard; moist dark yellowish brown 10YR3/4; sandy loam; medium sand; friable; slightly sticky; slightly plastic; none to few very fine and fine pores normal coating; 1 second water absorption; common roots; gradual tonguing transition.	Orthic
B1	400-800	Moist; mechanical undisturbed; moist yellowish brown 10YR5/6; sandy loam; fine sand; few medium distinct orange oxidized iron oxide mottles; apedal massive; slightly firm; slightly sticky; slightly plastic; few very fine and fine pores normal coating; very few rounded fine sesquioxide concretions/nodules; 1 second water absorption; few roots; clear smooth transition.	Yellow-brown apedal
B2	800+	Moist; mechanical undisturbed; moist brown 10YR5/3; sandy loam; fine sand; many medium prominent orange and red oxidized iron oxide mottles; weak fine subangular blocky; firm; slightly sticky; slightly plastic; many very fine and fine pores normal coating; few clay cutans; common rounded fine to medium sesquioxide concretions/nodules; 1 second water absorption; few roots.	Soft plinthic

Notes : Profile described outside on border of previous trial area. At time of classification planted with maize by farmer.

Farmer	:	Gerrit Roos
Farm	:	Leeubank
Telephone	:	083 635 3873

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Belfast - P source

Lab no	Depth	Horizon	Texture fractions (%)							Electric conductivity
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4822	0-400	A	13.8	10.9	6.0	27.0	5.1	19.9	16.4	21.5
4823	400-800	B1	15.7	9.0	5.7	28.6	4.3	14.7	22.6	13.0
4824	800+	B2	20.5	7.5	6.8	25.7	3.7	13.5	22.8	14.8

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												(cmol$_c$ kg^{-1})	
4822	14	86	0	0	0	0	0	0	0	0.532	0.140	0.002	7.000	0.041
4823	79	21	0	0	0	0	0	0	0	0.608	0.163	0.000	1.506	0.642
4824	78	22	0	0	0	0	0	0	0	0.434	0.095	0.000	1.796	0.665

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4822	7.18	6.60	9.43	5.61	50	1096	162	4	1.63	7	2	115	0.953	0.070	0.59
4823	4.48	3.99	2.24	0.63	26	94	39	1	3.50	1	1	55	0.277	0.030	42.62
4824	4.43	3.99	3.93	2.02	53	43	94	1	2.93	1	1	31	0.158	0.026	37.02

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	1335	1585	1503
15-30	1572	1512	1532
30-60	1565	1608	1594

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Calculated from over row and between row volumes at 0.9 m row widths as practised in area

Appendix 3.1 continued

Profile description

Profile No	:	**Vrede - P source**	Soil form	:	Klapmuts
Land type map	:	2728 Frankfort	Soil family	:	Napier
Latitude/Longitude	:	27°32'14" S/29°11'46" EO	Terrain unit	:	3 Upper
Land type No	:	Ea93a	Slope	:	4%
Elevation	:	1679 m	Slope shape	:	Convex
Climate zone	:	30G	Aspect	:	East
Vegetation	:	Agronomic cash crop (maize)	Water table	:	None
Described by	:	RW Bruce & CJJ Schmidt	Stoniness	:	None
Date described	:	2001-06-29	Erosion	:	None

Parent and underlying materials

Profile : On border between intrusive dolerite rocks from the Jurassic period and fine- to coarse-grained sandstone and grey shale (sedimentary and volcanic rocks) from the Normandien to Estcourt Formation, Adelaide Sub-Group and Beaufort Group during the Permian period (Muntingh, 1987).

Land type : One or more of vertic, melanic and red structured diagnostic horizons with undifferentiated soils. Geology is made up by mudstone, shale, sandstone and possibly grit of the Beaufort Group - Karoo Sequence. Ecca shale, sandstone and grit in the north. Dolerite sills abundant. It occurs on B4 terrain units. Demarcated on map 2728 Frankfort and situated in climate zone 30G (Schoeman, Bruce & Turner, 1984; Unpublished data from Land Type Survey, by R.W. Bruce & J.L. Schoeman.).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-300	Dry; mechanical disturbed; dry dark grayish brown 10YR4/2; hard to very hard; moist very dark greyish brown 10YR3/2; sandy loam; fine sand; apedal massive; friable; sticky; slightly plastic; few very fine and fine pores normal coating; very few fine to medium rounded sesquioxide concretions/nodule; 4 seconds water absorption; common roots; clear wavy transition.	Orthic
E	300-340	Dry; mechanical undisturbed; dry grayish brown 10YR5/2; soft; *texture not determined*; apedal massive; none to few very fine and fine pores; many medium rounded sesquioxide concretions/nodules; many gravel rock fragments and coarse gravel; single stone line 40 mm thick throughout horizon; 1 second water absorption; many roots; clear wavy transition.	E horizon
B	340-500	Dry; mechanical undisturbed; dry very dark grey 10YR3/1; hard to very hard; moist very dark grey 10YR3/1; sandy clay loam; fine sand; common fine faint orange and red oxidized iron oxide mottles; strong medium to coarse angular blocky structure; firm; sticky to very sticky; plastic; few very fine and fine pores normal coating; many clay and organic cutans; few to common gravel rock fragments and coarse gravel; 6 seconds water absorption; common roots; gradual tonguing to wavy transition.	Pedocutanic
C	500+	Dry.	Unspecified

Notes : E horizon is too thin to determine consistency and to collect sufficient soil for analyses.

Profile described within formerly trial area. At time of classification planted with pastures.

Farmer : Hannes Oosthuizen
Farm : Wapad
Telephone : 058-9131922

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Vrede - P source

Lab no	Depth	Horizon	Texture fractions (%)							Electric
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	conductivity
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	($mS\ m^{-1}$)
4838	0-300	A	18.5	4.7	8.4	25.3	8.2	12.6	20.6	16.8
-[1]	300-340	E	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]
4839	340-500	B	28.5	9.2	8.0	18.9	11.9	9.1	14.2	26.9

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												($cmol_c\ kg^{-1}$)	
4838	21	64	15	0	0	0	0	0	0	0.447	0.080	0.024	4.947	0.081
-[1]	4	88	5	0	0	3	0	0	0	0.738	0.123	0.052	-[1]	-[1]
4839	28	35	25	0	12	0	0	0	0	0.894	0.181	0.109	8.979	0.058

Lab no	$pH(H_2O)$	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			($mg\ kg^{-1}$)										(%)		
4838	5.44	4.62	7.61	5.47	85	675	154	1	2.61	15	3	313	1.092	0.110	1.64
-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]
4839	5.85	4.71	1.95	0.65	60	1169	314	78	2.97	7	2	68	0.780	0.095	0.65

Bulk density ($kg\ m^{-3}$)

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-150	-	-	1477****

[1] - All of the soil sample from the E-horizon was needed for mineralogical analysis and none remain for other analysis. Soil from the E-horizon was almost impossible to collect due to thin dimension, stoniness and roots.

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Measured

****- Deeper measurements not possible

Profile description

Profile No	:	**Dirkiesdorp - N x P x K**	Soil form	:	Shortlands
Land type map	:	2730 Vryheid	Soil family	:	Empangeni
Latitude/Longitude	:	27°07'52" S/30°21'34" EO	Terrain unit	:	3 Upper
Land type No	:	Bb36b	Slope	:	0.5%
Elevation	:	1370 m	Slope shape	:	Straight
Climate zone	:	111 S	Aspect	:	East
Vegetation	:	Agronomic cash crop (maize)	Water table	:	None
Described by	:	RW Bruce & CJJ Schmidt	Stoniness	:	None
Date described	:	2001-06-28	Erosion	:	None

Parent and underlying materials

Profile :	Sandstone, shale and grit with coal and oil-shade beds (sedimentary and volcanic rocks) of the Vryheid Formation and Ecca Group of the Karoo Sequence during the Permian period (Wolmarans, 1988).
Land type :	Plinthic catena with upland duplex and margalitic soils rare and dystrophic and/or mesotrophic red soils not widespread. Geology is made up by mainly sandstone of the Vryheid Formation - Ecca Group, with dolerite. Small areas of alluvium and shale of the Pietermaritzburg Formation - Ecca Group, metaquartzite and banded ironstone of the Five Tree Group. Dunite and pyroxenite also occur. It occurs on A3 terrain units. Demarcated on map 2730 Vryheid and situated in climate zone 111S (Turner, Smith-Baillie, Fitzpatrick, Plath & Vivian, 1985; Land Type Survey Staff, 1986).

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0-280	Moist; mechanical disturbed; moist dark reddish brown 5YR3/4; clay; medium sand; apedal massive; slightly firm; very sticky; plastic; few clay cutans; few very fine and fine pores normal coating; fine cracks; 6 seconds water absorption; few roots; gradual smooth transition.	Orthic
B1	280-800	Moist; mechanical undisturbed; moist yellowish red 5YR4/8; clay; fine sand; few fine faint red oxidized iron oxide mottles; moderate fine subangular blocky structure; firm; very sticky; plastic; few to common clay cutans; few very fine and fine pores normal coating; fine to medium cracks; very few fine rounded sesquioxide concretions/nodules; very few gravel rock fragments and coarse gravel; single stone line 30 mm thick in middle part of horizon; 2 seconds water absorption; few roots; diffuse wavy transition.	Red structured
Bc	800-1230	Moist; mechanical undisturbed; moist dark red 2.5YR3/6; clay; fine sand; few to common fine to medium faint red oxidized iron oxide mottles and ghosts of pebbles; moderate fine subangular blocky structure; firm; very sticky; plastic; common clay cutans; few very fine and fine pores normal coating; 2 seconds water absorption; gradual wavy transition.	Transition (Red structured)
C	1230+		Unspecified material

Notes : Structure of B horizon in moist condition sufficient to be red structured. Bc horizon contains no coarse fragments, but only ghosts of pebbles. Because the pebbles are soft it is seen as part of the horizon and not as a separate feature.

Profile described within trial area.

Farmer : Pieter Pienaar
Farm : Eerste Geluk
Telephone : 017-7300035

Appendix 3.1 continued

Chemical, physical and mineralogical information

Locality : Dirkiesdorp - N x P x K

Lab no	Depth	Horizon	Texture fractions (%)							Electric conductivity
			Clay	Silt	Coarse silt	very fine sand	fine sand	medium sand	coarse sand	
	(mm)		<2μ	2-20μ	20-45μ	45-106μ	106-250μ	250-500μ	>500μ	(mS m^{-1})
4835	0-280	A	47.2	5.3	5.1	13.9	7.3	14.9	5.5	26.4
4836	208-800	B1	63.4	3.6	4.9	9.0	9.1	4.6	5.2	9.7
4837	800-1230	B2	54.7	4.0	4.6	11.6	14.5	6.1	6.4	5.4

Lab no	Mineralogy *									CBD - method			CEC	Exchangeable acidity
	Kt	Qz	Mi	St	Is	Go	Ct	Hm	Gb	Fe	Al	Mn		
	(%)												(cmol$_c$ kg^{-1})	
4835	66	19	0	0	0	15	0	0	0	3.350	0.772	0.005	5.408	0.171
4836	80	6	0	0	6	8	0	0	0	4.260	0.899	0.005	2.044	1.035
4837	79	10	0	0	4	7	0	0	0	3.280	0.648	0.019	3.390	2.596

Lab no	pH(H_2O)	pH(KCl)	Exchangeable cations										Org C**	Tot N	AS
			Bray I	Ambic I											
			P	P	K	Ca	Mg	Na	Zn	Mn	Cu	Fe			
			(mg kg^{-1})										(%)		
4835	5.26	4.57	18.76	9.67	35	870	96	1	3.84	4	4	74	1.568	0.119	3.16
4836	4.57	4.29	0.56	0.01	19	132	36	1	1.36	5	2	28	0.555	0.055	50.63
4837	4.55	4.11	0.77	0.01	20	50	59	1	3.71	4	1	22	0.180	0.038	76.58

Bulk density (kg m^{-3})

Depth (mm)	Over rows	Between rows	Over plus between rows***
0-15	-	-	1285
15-30	-	-	1379
30-60	-	-	1258

* - Kt = Kaolinite; Qz = Quartz; Mi = Mica; St = Smectite; Is = Interstratified minerals; Go = Goethite; Ct = Calcite; Hm = Hematite; Gb = Gibbsite

** - Not factorized by 1.3

*** - Measured

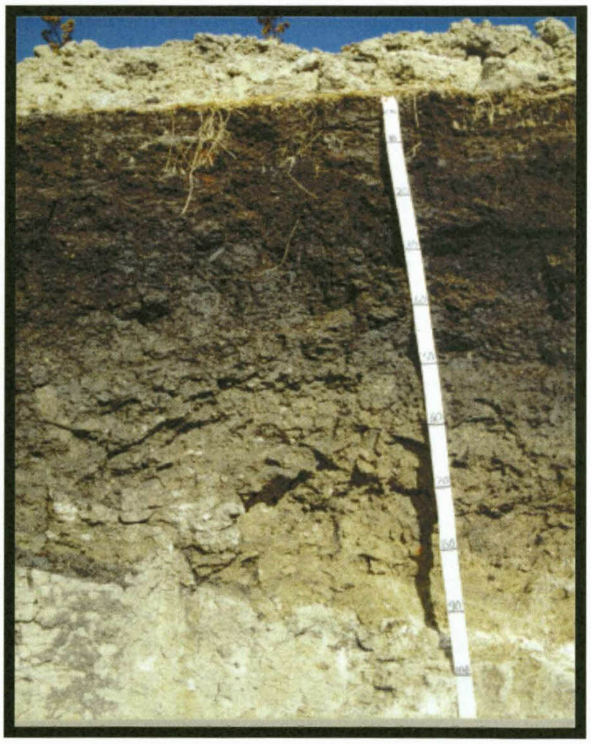
Appendix 3.2 : Pictures of soil profiles

Lichtenburg - road side

Lichtenburg - veld side

Wolmaransstad

Koppies



Appendix 3.2 continued

Ventersdorp

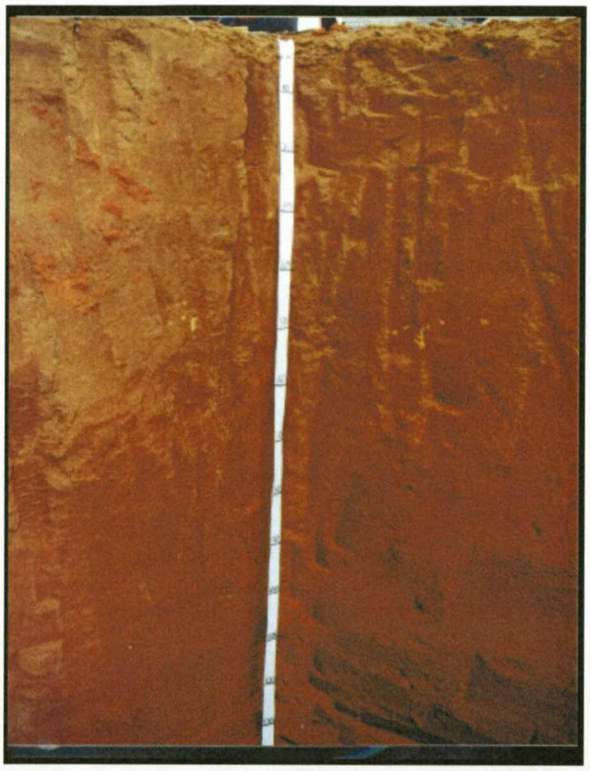
Viljoenskroon

Stilfontein

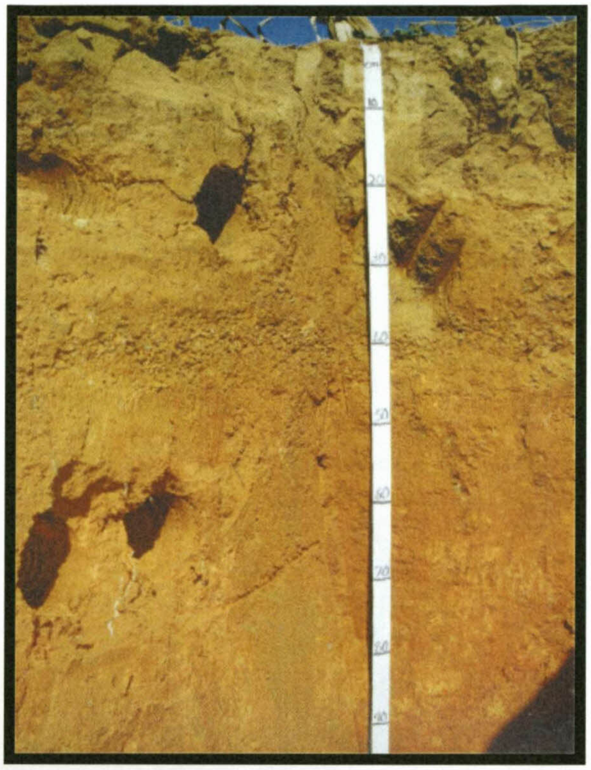
Heidelberg - N x P

Appendix 3.2 continued

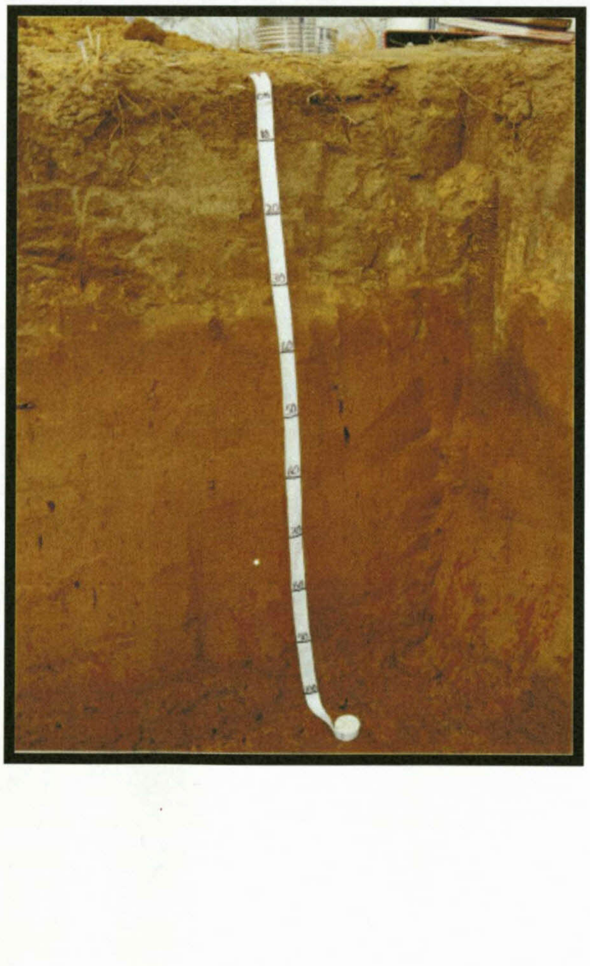
Heidelberg - Lime x P



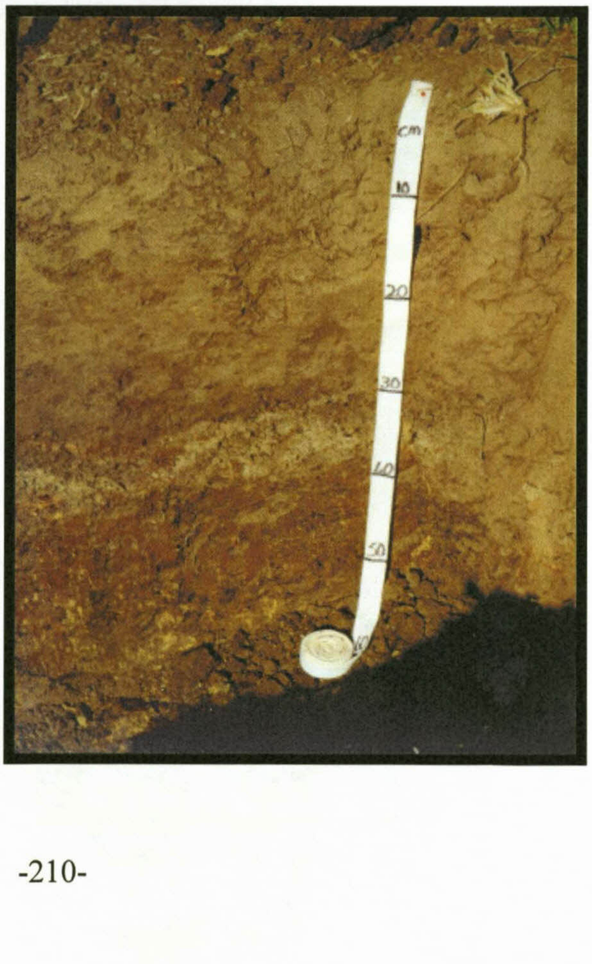
Athole



Belfast



Vrede

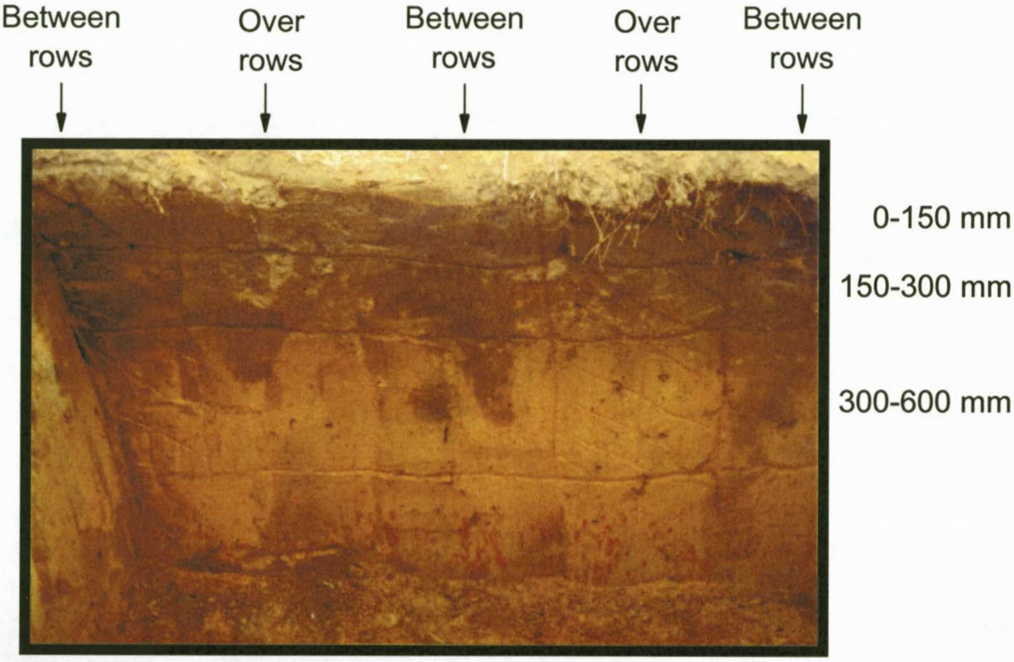


Appendix 3.2 continued

Dirkiesdorp

Appendix 3.3 : Soil sampling procedure used for the determination of bulk density at depths of 0-150, 150-300 and 300-600 mm over and between maize rows

Step 1 : Marking out soil volumes



Step 2 : Collecting samples