



# ***Rejuvenating soils with Minplus<sup>TM</sup>***

***A rock dust and soil conditioner  
to improve the productivity of  
acidic, highly weathered soils***

**A report for the Rural Industries Research  
and Development Corporation**

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*Rejuvenating soils with Minplus<sup>TM</sup>: a rock dust and soil conditioner to improve the productivity of acidic, highly weathered soils.*

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# Foreword

This project aimed to develop soil amendments from finely ground basaltic rock dust and to test their efficiency as ameliorants of the properties of acidic and highly weathered soils. The research products are intended to overcome the constraints to plant growth induced by low soil cation exchange capacities, strong soil acidity, and high phosphorus fixation capacities, all of which are commonly encountered in the soils of the humid tropics.

Major potential benefits to be derived from the application of the results of the project include:

- more sustainable uses of soil resources and fertilisers for improved plant growth;
- lower fertiliser use and import replacement as a result of diminished use of high-cost imported fertilisers;
- decreased nutrient losses from farmlands and reduced eutrophication of natural wetlands and marine systems;
- enhancement of a burgeoning rural manufacturing industry, and significant growth in both domestic and international markets for value-added materials.

This project was funded from RIRDC Core Funds which are provided by the Federal Government. It was developed in close collaboration with, and support from a small rural manufacturing company, Pacific Mineral Developments Pty Ltd.

This report, a new addition to RIRDC's diverse range of over 700 research publications, forms part of our Resilient Agricultural Systems Research and Development program which aims to enable agricultural production systems that have sufficient diversity, flexibility and robustness to be resilient and respond to challenges and opportunities.

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**Peter Core**  
Managing Director  
Rural Industries Research and Development Corporation

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Mrs Diane Bailey, Resources Office, James Cook University, provided valuable and highly appreciated reports and advice on managing financial issues throughout the project.

Professor Richard Pearson, Head, School of Tropical Biology, James Cook University, Townsville, made available laboratories, offices, and shadehouses where the bulk of the project activities were performed.

We take much pleasure in acknowledging the guidance and experience of a lifetime's work in plant physiology that Adjunct Professor Peter Brownell has offered in conducting the project and sharing in the supervision of various research student activities.

We appreciate and value the efforts of the staff of the Johnstone College of TAFE, Innisfail, for their assistance to the project in many ways. We are especially grateful to Ms Julia Thaggard, Director, whose interest and enthusiasm for the project resulted in securing land for the field experimental site, and to Mr Steve Bright, Horticulturalist, for his unstinting and tireless efforts to establish and maintain the site.

The field and laboratory work was assisted in many ways by the help of colleagues, friends, and coerced family members. Thank you everyone – you know who you are!

All the rock dust materials used in this project were supplied by the manufacturer, Pacific Mineral Developments Pty Ltd, P.O. Box 594, Innisfail, Queensland 4860; phone: 07 4064 4118, fax: 07 4064 4131, email: minerals@internetnorth.net.au).

The Manager of Pacific Mineral Developments, Mr Sam Catalano, has introduced the research team to fascinating scientific issues raised by his enthusiasm for using waste products from one industry to benefit another. Many of the research questions addressed by the project have been generated in trying to find answers to his questions about how Minplus<sup>TM</sup> works as a conditioner in the soil. We thank you, Sam, for the lessons you have taught us about the value of astute observations, innovative and critical thinking, perseverance, good humour, and rock dusts.

# Glossary of terms

Term	Definition
Absorption	The taking up of a gas or liquid by a liquid or solid to result in a uniform solution of the former in the latter. Absorption is the common process by which plants take in gases, water, nutrients, or other substances (Glendinning 2000). The process may be confused with ‘Adsorption’ (see below).
Acid soil	Soil containing a prevalence of hydrogen ions in the soil solution (active acidity), and hydrogen and / or aluminium ions on the surfaces of the colloids (reserve, or potential acidity). Specifically, a soil with a pH value of less than 7 (Glendinning 2000).
Acidic cations	The elements hydrogen and aluminium that held in the soil solution in ionic or positively charged forms: $H^+$ and $Al^{3+}$ .
Acidity, active	Measured and expressed as soil pH, which is the negative logarithm of the hydrogen ion activity in a soil. The degree of acidity (or alkalinity) of a soil expressed in terms of the pH scale. See ‘pH’.
Acidity, reserve	The amount of $H^+$ and $Al^{3+}$ that can be released into the soil solution by cation exchange (also referred to as “potential acidity”). See ‘pH’.
Adsorption	Attraction of ions or compounds to the surface of a solid.
AEC	See ‘Anion exchange capacity’
Aluminium oxides and oxyhydroxides	Minerals consisting of aluminium, oxygen, and hydroxyl [OH] groups that are commonly found in a very fine grained form in highly weathered soils. With increasing intensity of weathering, kaolinite clays $[Al_4(Si_4O_{10})(OH)_8]$ are progressively transformed into gibbsite $[Al(OH)_3]$ , which is transformed into boehmite $[AlO(OH)]$ , then diasporite $[HAlO_2]$ .
Amendment	See ‘Soil amendment’
Anions	Elements or compounds held in the soil solution in anionic or negatively charged forms; phosphate anions are extremely important in sustaining plant growth, especially in soils of the humid tropics.
Anion exchange capacity (AEC)	The sum of anions that can be adsorbed onto positively charged sites on the surfaces of colloids.
Anoxic conditions	Environmental conditions characterised by a lack of freely available oxygen, often occurring in waterlogged soils.
Availability	A general expression that refers to the ease with which plants can take up a particular nutrient from the soil. Different fractions within the total nutrient pool will have different availabilities, depending on factors such as solubility, and rates of dissolution and diffusion through the soil to the root (Peeverill <i>et al.</i> 1999).
Available nutrient	The amount of nutrient in the soil that can be taken up by a specified plant (Peeverill <i>et al.</i> 1999).

Term	Definition
Basalt	Dark coloured, fine grained volcanic rock consisting predominantly of minerals that are silicates of calcium, magnesium, iron, and potassium. The minerals include augite, plagioclase feldspar, olivine, and magnetite with minor orthoclase feldspar and apatite, a calcium phosphate.
Baseline soil samples, Innisfail field trial	Soil samples collected in July 1998, before any treatments were applied to the field trial site at the Johnstone College of TAFE, Innisfail (Chapter 4). The samples provide a baseline for comparing the effects of all the subsequently imposed experimental treatments.
Basic cations	Basic elements in the soil in cationic or positively charged form; those of interest are calcium, magnesium, potassium and sodium ( $\text{Ca}^{2+}$ , $\text{Mg}^{2+}$ , $\text{Na}^{+}$ , and $\text{K}^{+}$ , respectively).
‘Blend 3’	A commercially available soil conditioner consisting of finely ground dolomitic lime [ $\text{Ca}_{0.97}\text{Mg}_{0.03}\text{CO}_3$ ] consisting mainly of calcium carbonate [ $\text{CaCO}_3$ ] and 3% magnesium carbonate [ $\text{MgCO}_3$ ]. See ‘Dolomite’.
Brownell nutrient solution	A solution consisting of a mixture of essential plant macronutrients and micronutrients in concentrations specified by Brownell (1979) that are just sufficient to support the growth of most plants.
Buffering	Processes that constrain or reduce the change in pH when acids or bases are added to the soil. More generally, processes that constrain changes in the dissolved concentration of any ion when it is added to or removed from the system (Glendinning 2000).
Bulk density	The oven-dry (105 °C) mass of the soil per unit volume, usually expressed as $\text{g} / \text{cm}^3$ which yields numerical values equivalent to those of the SI unit of tonnes / $\text{m}^3$ . The higher the bulk density of the soil, the more dense and compacted it will appear to be.
Cations	Elements or compounds held in the soil solution in cationic or positively charged forms. Those of most interest in soils are the basic cations: $\text{Ca}^{2+}$ , $\text{Mg}^{2+}$ , $\text{Na}^{+}$ , and $\text{K}^{+}$ ; and the acidic cations: $\text{H}^{+}$ and $\text{Al}^{3+}$ .
Cation exchange	The interchange between a cation in the soil solution and another cation on the surface of a material such as a clay mineral or fine, organic colloid (Glendinning 2000).
Cation exchange capacity (CEC)	The sum of cations that can be adsorbed onto negatively charged sites on the surfaces of colloids. The CEC of a soil provides an indication of its fertility. See also ‘Effective cation exchange capacity (ECEC)’ and ‘Net negative charge’.
$\text{CEC}_B$	Basic cation exchange capacity of a soil equal to the measure of surface negative charge of the soil. $\text{CEC}_B$ is determined by $\text{Ca}^{2+}$ adsorption following the method of Gillman and Sumpter (1986b).
$\text{CEC}_T$	Total cation exchange capacity of a soil equal to the measure of surface negative charge of the soil. $\text{CEC}_T$ is determined by $\text{Ca}^{2+}$ and $\text{Al}^{3+}$ adsorption following the method of Gillman and Sumpter (1986b).
Chlorosis	An abnormal condition of plants in which the green parts lose their colour or turn yellow (Glendinning 2000)

Term	Definition
Clay	A general term for colloid sized ( < 0.002 mm) fine particles of inorganic (mineral) origin in soils
Clay mineral	<b>Aluminosilicate minerals</b> that are fine-grained, plate-like in form, and composed of layers of atoms arranged in 1 sheet with tetrahedral arrangements of SiO <sub>4</sub> groups and sheets of other atoms with an octahedral arrangement (Brady 1984). The <b>1:1 clay minerals</b> (e.g. kaolinite and halloysite) have stable crystal structures and do not swell or shrink with moisture changes; they consist of 1 tetrahedral and 1 octahedral layer. The <b>2:1 clays</b> (e.g. the mica-like clay mineral illite; chlorite, vermiculite; and the smectites such as montmorillonite and bentonite) have 2 octahedral layers of different compositions to 1 tetrahedral layer. Some of the 2:1 clay minerals, especially the smectites, swell and shrink to different extents in response to moisture changes in the soil.
cmol/kg, or cmol <sub>c</sub> /kg	Centimoles of charge/kg of soil, which is the SI unit of measurement of the cation or anion contents of a soil. Values are numerically equivalent to the non-SI units of milliequivalents/100 g of soil (meq/100 g), or milliequivalents % (meq %).
Colloid	Materials of organic (“humus”) or inorganic (“clay”) composition and less than 0.002 mm in diameter. Colloids are very fine-grained materials with a large surface area and are very reactive in the soil.
Conditioner	See ‘Soil conditioner’.
Control	Soil or plants grown in the soil of an experimental plot or pot that has not been treated with any ‘Minplus <sup>TM</sup> ’, other soil conditioner, or fertiliser. Controls provide a standard against which to measure changes induced in the treatments applied to other soils or pots in the experiment.
Control CO	A control receiving no nutrients, used in the Innisfail Clay pot trial (Chapter 6), consisting of untreated and unincubated soil, provided with water only.
Control CL	A ‘low nutrient control’, used in the Innisfail Clay pot trial (Chapter 6), consisting of untreated and unincubated soil and watered with a nutrient solution at 50% of the concentration of a Brownell nutrient solution (see ‘Brownell solution’).
Control CH	A ‘high nutrient control’, used in the Innisfail Clay pot trial (Chapter 6), consisting of untreated and unincubated soil and watered with a nutrient solution at 150% of the concentration of a Brownell nutrient solution (see ‘Brownell solution’). A relatively high concentration of nutrients was used to overcome some of the tendency of the colloids in the soil to sorb or fix the applied nutrients.
DAP	See ‘Diammonium phosphate’.
Deprotonation	The processes occurring in alkaline solutions where ‘hydroxylated mineral surfaces’ (see below) lose H <sup>+</sup> ions to the soil solution.
Diammonium phosphate	DAP: a phosphatic fertiliser that also contains nitrogen [(NH <sub>4</sub> ) <sub>2</sub> HPO <sub>4</sub> ].
Dolomite	A mineral composed of calcium and magnesium carbonate [CaMg(CO <sub>3</sub> ) <sub>2</sub> ].

Term	Definition
Dolomitic lime	A term applied to crushed limestone that contains some magnesium. See 'Dolomite' and 'Blend 3'.
Effective cation exchange capacity (ECEC)	The effective cation exchange capacity of the soil determined as the sum of the exchangeable basic and acidic cations. See 'Cation exchange capacity'. $\text{ECEC} = (\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^{+} + \text{K}^{+} + \text{H}^{+} + \text{Al}^{3+})$
Electrical charges on soil particles	Soil particles may have a permanent charge (i.e. induced by isomorphic substitution of cations in crystal structures) or variable charge that is dependent on soil pH. Positive or negative surface charges on soil colloids influence the capacity of the colloid to retain or release plant nutrient ions. The charges are affected by such factors as the 'size' or ionic radius of the cations and anions, their valencies, $\text{H}^{+}$ -ion activity in the soil solution, and the structures of clay mineral lattices (Glendinning 2000).
Electrical conductivity (EC)	The electrical conductivity of the soil measures of the amount of soluble salts in the soil solution. Soil EC is expressed in millisiemens/cm ( $\text{mS/cm} = \text{dS/m}$ ) and ranges of 750 to 3000 $\text{mS/cm}$ will allow plant growth, unless the plant species is salt intolerant.
Equivalent weight	The weight in grams of an ion or compound that combines with, or replaces 1 gram of hydrogen (Glendinning 2000). The equivalent weight of an ion is its atomic weight or formula weight divided by its valence.
Essential plant nutrients	The 17 elements that must be present in adequate amounts in the soil to permit plant growth. An element is regarded by Salisbury and Ross (1992) as "essential" if: <ul style="list-style-type: none"> <li>the plant cannot complete its life cycle (i.e. form viable seeds) in the absence of the element;</li> <li>the essential element forms part of any molecule or constituent of the plant that is itself essential in the plant: e.g. nitrogen in proteins; magnesium in chlorophyll;</li> <li>the essential element must be acting directly inside the plant and not causing some other element to be more readily available or antagonising the effect of another element. For example, the growth-promoting effects of non-essential selenium are thought to result from the ability of the selenate ion to inhibit the absorption of phosphate, which otherwise is absorbed by plants in toxic amounts.</li> </ul> See 'Macronutrients' and 'Micronutrients'.
Eutrophication	The enrichment in nutrients of wetlands, riparian, and marine environments resulting in abundant growth of aquatic plants and low oxygen levels in the waters.
Exchange capacity	See 'Cation exchange capacity' and 'Anion exchange capacity'.
Exchangeable cation	A positively charged ion held on or near the surface of a solid particle by the negative surface charges on the colloid and which may be replaced by other positively charged ions in the soil solution (Peverill <i>et al.</i> 1999).
Exchange complex	All the materials, primarily inorganic clays or organic humus, that contribute to the cation exchange capacity of the soil (Glendinning 2000).
Exchangeable bases	See 'Basic cations'.



Term	Definition
Fertiliser	A source of essential macronutrients and / or micronutrients that are added to the soil for uptake by growing plants. In the field trials on the Innisfail Clay (Chapter 4), phosphatic fertilisers were added at the time of planting to the soils that had previously been conditioned with lime, cement, or Minplus™ applications. See ‘Soil conditioner’.
Fertiliser requirement	The quantity of certain plant nutrients needed, in addition to the amount supplied from the soil, to increase plant growth to a designated level (Peverill <i>et al.</i> 1999).
Fertility, Soil	The status of the soil with respect to the amount and availability to plants of nutrient elements that are essential for plant growth (Glendinning 2000).
Field capacity	The amount of water remaining in the soil after it has been saturated and allowed to drain for 48 hours (Miller and Donohue 1995). The determination provides a measure of the maximum amount of plant-available water that may be held in the soil.
Fixation	The process by which available plant nutrients are rendered unavailable by reactions with soil components (Glendinning 2000). The term commonly refers to the reactions in highly weathered soils that remove phosphorus (applied in phosphatic fertilisers) from the soil solution and thereby make the element unavailable to be taken up by plants by absorption from the soil water.
Free ferric oxide	Iron oxides occurring in the soil in a finely crystalline or amorphous form and not combined with other elements.
Furnace slag	A mixture of calcium silicates of the general form of $\text{CaSiO}_3$ and / or $\text{CaSiO}_4$ , some with phosphorus, $\text{CaO}$ , and $\text{Ca(OH)}_2$ . Slags are the by-products of the iron manufacturing industry.
Granite	A coarse grained, light coloured igneous rock which consists predominantly of silicates of aluminium, potassium and sodium: quartz, orthoclase and plagioclase feldspars, hornblende, and biotite mica. Rock dusts produced from granitic sources provide few essential plant elements to the soil and have been shown to be of little value as slow release fertilisers in the sandy soils of Western Australia (Bolland and Baker 2000).
Gypsum	Calcium sulphate [ $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ]
Hectare (ha)	hectare: 1 ha = 100 x 100 m = 10,000 square metres = 2.5 acres
Highly weathered soil	<p>Highly weathered soils have undergone intense weathering and strong leaching of their mineral components because of their age, climatic setting, or both. The soils have lost most or all of their more mobile plant nutrients; their minerals represent residual concentrations of relatively immobile elements in the soil such as iron, aluminium, and titanium. As a consequence, highly weathered soils display a range of properties detrimental to plant growth, including:</p> <ul style="list-style-type: none"> <li>▪ lack of nutrient supplied from weatherable minerals,</li> <li>▪ rapid oxidation of organic matter leading to degeneration of soil structure,</li> <li>▪ reduced levels of exchangeable basic cations,</li> <li>▪ strong soil acidity,</li> <li>▪ low availability of, or high requirements for phosphorus,</li> <li>▪ inability to respond to liming,</li> <li>▪ restricted micro-organism activity,</li> <li>▪ low levels of calcium and magnesium.</li> </ul>

Term	Definition
Histosol	A group of soils of the US Soil Taxonomy that is characterised by high contents (> 20 %) of organic matter to a depth of at least 40 cm, that have accumulated in moist conditions – usually in peat bogs or swamps.
Humus	Colloidal particles (diameter < 0.002 mm) of organic origin. See ‘Colloid’ and ‘Clay’.
Hydrated	Ions or compounds having water attached or incorporated as part of their chemical structures (Glendinning 2000).
Hydrated lime	A caustic liming agent that is formed from quicklime that has reacted with water. Also known as ‘slaked lime’ $[\text{Ca}(\text{OH})_2]$
Hydroxylated mineral surfaces	Electrostatically charged mineral surfaces to which have been attracted $\text{OH}^-$ anions from the soil solution.
Incomplete bonding	Chemical bonds formed by atoms in compounds or minerals that are fewer than those theoretically possible according to the valency of the atom.
Incubation (of soil)	The process of mixing a soil conditioner into the soil, adding water to the field capacity of the soil, and setting aside for a period of time for reactions to occur in the moist state. Soils for pot trials may be incubated in sealed plastic bags at room temperature. Field trial soils may be incubated by adding the soil conditioner to the soil, cultivating, and allowing the soil to lie fallow under natural conditions for the incubation period.
Iron oxides and oxyhydroxides	Minerals consisting of iron, oxygen, and hydroxyl groups that occur in a very fine grained or amorphous form in soils. These minerals impart characteristic red colours [hematite $\text{Fe}_2\text{O}_3$ ] to soils of well drained sites, and yellow colours [goethite $\text{FeO}(\text{OH})$ ] to those of more poorly drained sites.
Kaolinite	A clay mineral with a 1:1 sheet structure and consisting of aluminium, silicon, oxygen and hydroxyl groups: $\text{Al}_4(\text{Si}_4\text{O}_{10})(\text{OH})_8$ .
Leaching	The removal of materials in solution from the soil by percolating waters (Brady and Weil 1999).
Lime	Calcium carbonate $[\text{CaCO}_3]$ , derived from finely ground calcitic limestone. Lime is an agent used to neutralise the acidity of soils, but liberates 400 kg of the greenhouse gas carbon dioxide for every tonne of lime applied to the soil.
Molarity, Molar (M)	Molarity: a measure of the concentration of a solution. A 1 M solution contains 1 mole (i.e. the atomic weight or formula weight in grams) of the solute in 1 litre of water.
Macronutrients	<p>The 9 essential plant elements needed by plants in relatively large amounts. They are:</p> <ul style="list-style-type: none"> <li>hydrogen [H], carbon [C], and oxygen [O] which are readily supplied to the plant from water <math>[\text{H}_2\text{O}]</math> and from oxygen and carbon dioxide <math>[\text{CO}_2]</math> from air;</li> <li>nitrogen [N], phosphorus [P], and potassium [K], which are the chief constituents of N-P-K fertilisers;</li> <li>calcium [Ca], magnesium [Mg], and sulphur [S], which are often supplied as additives in inorganic fertilisers.</li> </ul> <p>See ‘Essential elements’ and ‘Micronutrients’.</p>
me %, meq %, meq / 100 g	The unit is a measure of the charge carried on the surfaces of soil colloids and is numerically equal to units expressed in SI units as cmol/kg. See ‘cmol /kg’.

Term	Definition
Micronutrients	The 8 essential elements needed by plants in relatively small amounts, hence their alternative name “trace elements”. They include: chlorine [Cl], iron [Fe], boron [B], manganese [Mn], zinc [Zn], copper [Cu], nickel [Ni], and molybdenum [Mo]. See ‘Essential elements’ and ‘Macronutrients’.
Minplus <sup>TM</sup>	A soil conditioner made from finely crushed basaltic rock. The product consists largely of calcium and magnesium silicates, small amounts of phosphorus and potassium, and abundant trace elements. Minplus <sup>TM</sup> used in the present project was supplied by the manufacturer, Pacific Mineral Developments Pty Ltd, P.O. Box 594, Innisfail, Queensland 4860; phone: 07 4064 4118, fax: 07 4064 4131, email: minerals@internetnorth.net.au
Modifier	See ‘Soil modifier’
Mollisol	A US Soil Taxonomy group of dark coloured, deep, highly fertile soils of semiarid to moist grasslands and prairies with high contents of basic cations.
Necrosis	Death of part of the living tissue of a plant (Peverill <i>et al.</i> 1999)
Negative charge of soil	The amount of positive or negative charge per unit area of the surface of a colloid is called the charge density, (meq / cm <sup>2</sup> ). The product of the specific surface area of the soil colloid S (cm <sup>2</sup> / g) and is the total amount of charge present in the soil. The negative charge of the soil is directly related to the cation exchange capacity of the soil CEC (meq / g), as follows: CEC = S (Uehara and Gillman, 1981, p.42). See ‘Electrical charge on soil particles’, Permanent surface charge’, and ‘Variable surface charge’.
Neutralising value	The relative ability of various liming agents to counteract soil acidity, as compared to pure calcium carbonate [CaCO <sub>3</sub> ], which is expressed at 100 (Tisdale <i>et al.</i> 1993).
Organic matter	Material derived from living or dead plant or animal residues in various stages of decomposition in the soil.
Oxisol	A US Soil Taxonomy group of soils characterised by residual accumulations of inactive clays, free oxides, kaolin and quartz. They are mostly found in strong weathering environments under humid tropical climates.
Permanent surface charge	The negative or positive charge of clay particles inherited from ionic substitutions in the crystal lattice of the particle; the surface charge is not affected by changes in soil pH or by ion exchange (Uehara and Gillman, 1981). See ‘Electrical charge on soil particles’, Negative charge of soil’, and ‘Variable surface charge’.
pH, Soil	See ‘Soil pH’.
Phosphate fixation	The ability of soil particles to adsorb phosphorus from phosphate anions to their surfaces and retain it against plant uptake or leaching. The fixation process takes the phosphate ions that are dissolved in the soil solution and immobilises (“fixes”) them as complexes or insoluble compounds on surfaces of reactive soil colloids. Phosphate fixation makes it extremely difficult for plant roots to take up phosphorus.
Phosphorus sorption	See ‘Phosphate fixation’

Term	Definition
Plant available elements	The fraction of the total amount of an element in the soil that is present in a soluble form in the soil solution and may be taken up by growing plants.
Podzol	Podzol soil profiles are common in siliceous dune sands of the humid, coastal regions of Australia. The soils are characterised by prominent, organic enriched, dark A1 horizons, overlying white, bleached, very strongly leached sandy A2 horizons that pass downwards into heavier textured B2 horizons in which iron, aluminium and soil organic matter have accumulated in various proportions (Thompson, 1981).
Portland cement	<p>Portland cement is used as a binder in concrete, concrete masonry, mortar, and grouts in the construction industry. The <i>Queensland Cement Limited, Material Safety Data Sheet, 11/11/98</i>, indicates that Portland cement is a mixture of:</p> <ul style="list-style-type: none"> <li>▪ calcium silicates 35 – 85%,</li> <li>▪ calcium aluminates 1 – 10%,</li> <li>▪ tetracalcium aluminoferrite 10 – 20%,</li> <li>▪ gypsum (calcium sulphate) 2 – 5%,</li> <li>▪ calcium carbonate 0 – 5%,</li> <li>▪ calcium oxide 0 – 3%,</li> <li>▪ magnesium oxide &lt; 3.5%</li> </ul> <p>Cement is manufactured from limestone and the process releases 1 tonne of carbon dioxide, a greenhouse gas, for every tonne of cement produced. Every year, the world produces some 2.5 billion tonnes of cement – approximately 1/3 of a tonne for every man, woman, and child on the Earth.</p>
ppm	‘ppm’ or ‘parts per million’ is a non-SI unit term that has been replaced by the SI unit ‘micrograms per gram’ ( g/g).
Protonation	The processes whereby hydroxylated surfaces may adsorb H <sup>+</sup> ions from the soil solution under acidic conditions.
Q-Phos	A type of rock phosphate containing mainly calcium fluorophosphates and / or calcium hydroxyapatites [Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F and Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> OH]. The Q-Phos used in the field trials at Innisfail (Chapter 4) were obtained from the Burdekin Lime Company, Ayr, and had been derived from a reworked tailings dam at the Phosphate Hill Mine at Duchess, northwestern Queensland. See ‘Rock phosphate’.
Quartz	The commonest rock-forming mineral, composed of silica [SiO <sub>2</sub> ], occurring in hexagon crystals (clear and colourless when pure) or cryptocrystalline.
Quicklime	Caustic, finely ground, burnt limestone [CaO].
Rock phosphate	A naturally occurring rock containing one or more phosphate minerals (usually the very slowly soluble calcium phosphate minerals), of sufficient purity and quantity to allow the crushed rock to be used as a source of phosphorus. See ‘Q-Phos’.
Silica	Silicon dioxide [SiO <sub>2</sub> ] , commonly occurring in nature in a crystalline form as quartz, or in an amorphous form as porcellanite, agate, or opal.
Silicate-based soil amendment	Soil conditioners that release silicon into the soil. They are usually ground finely before application to the soil and include: Minplus <sup>TM</sup> , other rock dusts, calcium silicate slags, fly ash, and Portland cement.
Silicate minerals	Minerals in which Si and O are essential components, and embracing most of the common rock-forming minerals.

Term	Definition
Silicate sheet	Plate-like structure of silicate mineral lattices containing repetitive arrangements of 1 silicon and 4 oxygen atoms in shared tetrahedral configurations (Singer and Munns 1992)
Silicon	A non-metallic element [Si]; the second most abundant on earth after oxygen.
Slaked lime	See 'Hydrated lime'.
Soil amendment	A substance added to the soil to improve its physical or chemical properties such as the Portland cement, Blend 3 (dolomitic lime) or 'Minplus <sup>TM</sup> ' added to the soil of the field trial on the Innisfail Clay to condition it before planting herbaceous legumes. These materials are discussed in Chapter 4. See 'Soil conditioner' and 'Fertiliser'.
Soil conditioner	Soil conditioners are substances that modify the properties of soils, especially their cation exchange capacities, acidity, and phosphorus fixation capacities, such that water and plant nutrients are made more readily available to the growing plants. Soil conditioners do not necessarily provide nutrients to plants, but change the properties of soils such that fertilisers may work more efficiently. See 'Soil amendment' and 'Fertiliser'
Soil modifier	Calcium, magnesium, and phosphorus compounds added only to the pot trial on the Innisfail Clay (Chapter 6).
Soil pH	A measure of acidity or alkalinity of the soil. The pH of the soil is equal to the negative logarithm of the hydrogen ion concentration in the soil. Soil pH is measured by using an electrode inserted into a 1:5 soil : water suspension ( $\text{pH}_w$ ), or into a weak solution of calcium chloride ( $\text{pH}_{Ca}$ ). Acid soils have $\text{pH}_w$ less than 6.5; neutral soils have $\text{pH}_w$ 6.5 – 7; alkaline soils have $\text{pH}_w$ greater than 7. Field test kits have been produced commercially and produce less accurate pH estimations based on colour changes of an indicator applied to the soil.
Soil solution	The aqueous phase of the soil and its solutes consisting of ions dissociated from the surfaces of the soil particles and of other soluble minerals (Brady and Weil 1999).
Sorb, Sorption	see 'Adsorption'
Specific surface area	The solid-particle surface area of a soil or porous medium divided by the solid-particle mass or volume, expressed in $\text{m}^2 \text{kg}^{-1}$ , or, $\text{m}^2/\text{m}^3 = \text{m}^{-1}$ , respectively (van Wambeke 1992).
Standard phosphate requirement	A basis for determining adsorbed phosphate at standard supernatant concentrations of phosphate which is, in turn, an estimate of the relative phosphate needs of soils to sustain plant growth (Fox and Searle 1978).
Standard phosphorus sorption capacity	See 'Standard phosphate requirement'.
Superphosphate	Single superphosphate containing calcium, phosphates and sulphates $[\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}]$ and $\text{CaSO}_4$ .
Surface charge density	The amount of charge on the surface of a soil particle ( ). See 'Net negative charge'.
t / ha	tonnes per hectare

Term	Definition
Ultisol	A US Soil Taxonomy group that has low contents of bases and sub-surface horizons of illuvial clay accumulations. The soils are usually moist, but are dry during part of the warm season of the year.
US Soil Taxonomy	A soil classification scheme developed by the US Soil Survey Staff (1975).
Variable surface charge	Electrical charge on clay or soil organic matter that changes with changes in soil pH (Singer and Munns 1987). See 'Electrical charge on soil particles', Permanent surface charge', and 'Negative charge on soil'.
Vertisol	A US Soil Taxonomy group consisting of soils that have high (> 30 %) clay contents and crack open in dry times of the year.
Volcanic glass	A reactive, amorphous mineral component of volcanic rocks that has formed by very rapid cooling of molten magma.
Wilting point	The point at which gravity is no longer of any significance in moving water in the soil. At this point, water remaining in the soil is held so tightly that the forces holding it in the soil are about that equal to the plant suction trying to remove it; plants are unable to remove any more of the soil water and start to wilt.
g	microgram = 0.000 001 of a gram
g / g	Unit of concentration equivalent, numerically, to parts per million (ppm).
m	'micron', or micrometre = one thousandth of 1 mm = 0.000 001 m
	Surface charge density. See 'Negative charge of soil'.

# Executive Summary

## **The problem: sustaining the productivity of highly weathered soils**

Highly weathered soils, characterised by intense weathering and strong leaching of their mineral components, display a range of properties that are indicative of low inherent fertility and conditions detrimental to plant growth, including:

- strong soil acidity,
- low contents of nutrient cations supplied from weatherable minerals,
- very low levels of plant nutrients in the form of exchangeable basic cations, especially calcium, magnesium, and potassium,
- low availability of, or high requirements for phosphorus,
- weak ability to respond to liming,
- rapid oxidation of organic matter leading to degeneration of soil structure, restricted soil micro-organism activity.

The present report focuses on the use of a finely crushed basaltic rock dust as a means of overcoming such problems in farming systems on highly weathered soils, especially those of the humid tropics of Australia.

## **Nature of Minplus™ rock dust**

The research was carried out into the nature and soil conditioning capacity of the finely ground basaltic rock dust manufactured and marketed as Minplus™ by our collaborative Industry Partner, Pacific Mineral Developments Pty Ltd, Innisfail. The feedstock, a rock quarry by-product passing through a 7 mm sieve, is finely ground in a ball mill to reduce the particle-size of the product to less than 0.250 mm. We found that this particle-size will release the maximum amount of exchangeable basic cations from the dust.

Minplus™ is a product that is entirely natural and is certified for use in organic farming systems. The rock dust reflects the composition of basaltic rocks, predominantly silicates of calcium, magnesium, iron, and aluminium, and is inherently more fertile than dusts derived from the granitic quarry by-products that are widely available in Australia.

The product provides abundant amounts of a number of macro- and micro-nutrients that are essential for plant growth (notably calcium, magnesium, sulphur, and trace elements: iron, manganese, zinc, and copper), but no nitrogen, and relatively low amounts of phosphorus and potassium. We found that the use of mineral additives from rock phosphate and alkali granite is an ineffective way of enhancing the phosphorus and potassium contents of the rock dust; such supplements would be best supplied by using conventional fertilisers. On the other hand, gypsum appears to have some potential as a sulphur supplement in crushed basaltic soil amendments.

## **Minplus™ as a soil conditioner**

We have studied the properties of seven important agricultural soils, formed in different soil parent materials in the Innisfail-Tully area (granite, basalt, metamorphic rocks, basaltic alluvium, granitic alluvium, and a sandy beach ridge), and have determined the extent to which Minplus™ applications have modified those soil properties. In these experiments, we used Standard grade Minplus™, finer than 0.250 mm, and a Superfine grade, finer than 0.040 mm, both at rates equivalent to applications of 0, 1, 2.5, 5, 25, and 50 t/ha. In particular, we have studied the effects of Minplus™ on soil acidity (pH), cation chemistry (exchangeable basic and acidic cation contents and enrichment on different parent materials, charge fingerprints, plant nutrients), phosphorus chemistry (phosphorus fixation capacity, plant available phosphorus), and silicon chemistry (extractable silicon using four different extractants).

We have demonstrated from field and pot trials that Minplus™ rock dust has the capacity to enhance plant growth in difficult, highly weathered soils whose properties combine to inhibit crop production. Our research has shown that this is accomplished by the ability of Minplus™ to:

- rejuvenate the mineral and chemical properties of highly weathered soils;
- improve the cation exchange capacity of the soil;
- enhance the ability of soils to retain nutrient cations in the soil;
- enhance the ability of soils to supply nutrient cations to plants;
- reduce soil acidity, similarly to the action of lime, but sustained against soil leaching in high rainfall terrains over a long time periods;
- neutralise soil acidity without the liberation of greenhouse gases, unlike lime which releases 400 kg of carbon dioxide from every tonne of lime applied to the soil. We note that some 2 million tonnes of agricultural lime is used annually in Australia (Merry & Janik, 1999, RIRDC Project No. CSO-9A), and this has the potential to release up to 800,000 tonnes of carbon dioxide in neutralising soil acidity;
- reduce phosphorus fixation capacity of the soil, so that phosphates added in fertiliser are kept in soil solution and are more readily available for plant nutrition;
- provide silicon to the soil for uptake into plant cells, which is thought to result in improved plant vigour and quality.

## **Longevity of the soil conditioning benefit**

The longevity of the beneficial effects of Minplus™ application was investigated in a laboratory leaching study of 7 Minplus™-treated soils, which were subjected to the equivalent of one wet season's rainfall at Innisfail (2,750 mm) applied over a six week period. Minplus™ applications produced a significant increase in cation exchange capacity of all the soils. The increase was sustained against leaching processes: after leaching, the soils showed no diminution in the increased amounts of exchangeable calcium that were derived from the Minplus™ treatments. Similarly, some 94% and 53% of the exchangeable magnesium and potassium contents were retained in the leached soils.

These results suggest that some of the important benefits of Minplus™ applications to soils may be retained against leaching of rainfall over a number of wet seasons. Continued monitoring of changes in the field trials that have been established on the Innisfail Clay will provide a field verification of these findings on at least one of the studied soils. Long-term trials are needed on other soils and



under different crop and vegetation covers to confirm the longevity of the benefits of Minplus™ applications to a wider range of soils and farming systems.

### **Broader benefits from the use of Minplus™**

From our research results, we conclude that the use of Minplus™ as a soil conditioner is expected to deliver following outcomes for farming systems on highly weathered soils:

- improved plant growth in acidic soils of low fertility;
- reduced fertiliser use in acidic soils with strong phosphorus-fixing properties;
- import replacement as a result of diminished use of high-cost imported fertilisers;
- reduced environmental hazards from decreased use of agricultural lime;
- reduced environmental hazards from decreased erosional losses of nutrients from farmlands and their deposition in sensitive natural wetlands and nearshore marine systems.

Hence, the product is thought to have the potential to provide significant commercial benefits through its ability to:

- enhance soil health and increase crop yields;
- reduce farming input costs in lower rates of application of fertiliser, and possibly pesticides;
- reduce the social, economic, and environmental impact of algal blooms and other evidence of high nutrient levels in waterways downstream of agricultural activities;
- provide divalent cations that may be used as a tool to be used in the amelioration of sodic soils;
- provide import replacement through the need for less fertiliser to sustain plant production on soils that have been treated with Minplus™ applications. This point is particularly significant in Far North Queensland, where fertiliser (70,000 tonnes in 1999) is second only to fuel in the scale of imports into the regional economy through the Port of Cairns;
- underpin the development of new farming strategies to ensure more sustainable uses of soil resources and fertilisers.

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# 1. Introduction

## 1.1 Soils and plant growth

The minerals occurring in soil parent materials are gradually broken down with the passage of time to release their constituent elements into the soil. Some of these elements are dissolved by waters leaching through the soil profile and are lost from the soil, others are removed in the soil particles that form the muddy component of runoff waters after rain, and others are taken up in a dissolved form by plant roots to sustain growth. Elements taken up by agricultural crops are removed upon harvesting and, together with the elements lost by leaching or soil erosion, dramatically alter the mineral balance of the soil. Thus, the mineral content of soils used to produce each successive crop undergo a steady decline which must be balanced by inputs of soil conditioners and fertilisers if the system is to remain viable and productive.

Successful growth of plants for pleasure or for profit depends on the availability of light, water, and a good supply of plant nutrients in the soil. Seventeen elements are essential for the growth of all plants; deficiencies of different severities will become evident in the growth of plants in soils that lack adequate supplies of the essential elements (Salisbury and Ross 1992). Of these, 8 elements known as “the macronutrients” are required in relatively large amounts. They include hydrogen [H], carbon [C], and oxygen [O] which are readily supplied to the plant from water [H<sub>2</sub>O] and from oxygen and carbon dioxide [CO<sub>2</sub>] from air. Other macronutrients include nitrogen [N], phosphorus [P], and potassium [K], which are the chief constituents of N-P-K fertilisers, and calcium [Ca], magnesium [Mg], and sulphur [S], which are often supplied as additives in inorganic fertilisers. The “micronutrients” are required by plants in very small amounts, hence their alternative name “trace elements”. They include chlorine [Cl], iron [Fe], boron [B], manganese [Mn], zinc [Zn], copper [Cu], nickel [Ni], and molybdenum [Mo].

Other elements have been shown to be beneficial, although not essential, to the growth of some plants. For example, sodium [Na] has been shown to be important in photosynthesis in C-4 and some CAM plants; cobalt [Co] is used by rhizobial bacteria in the nodulation of legumes; silicon [Si] strengthens cell walls in some plants, such as rice.

The presence of certain elements in the soil may be antagonistic to plant growth or detrimental to the quality of plant produce. For example, manganese [Mn] and aluminium [Al] may attain toxic levels in strongly acidic soils; heavy metals (cadmium Cd, lead Pb, mercury Hg) may be taken up from the soil and occur as toxic contaminants in fruits, vegetables, and field crops.

Weathering processes, mineral breakdown, and leaching losses are greatest in the humid tropical areas of the world where temperatures are high, there is abundant moisture in the soil, and chemical reactions proceed more rapidly than in the temperate zone. Macro- and micronutrient elements are lost from the rootzone of the plants; residual minerals that are resistant to weathering (mainly kaolinitic clays and iron and aluminium oxides and oxyhydroxides) tend to accumulate in the soil. The residual minerals yield little chemical benefit to plants. As weathering, leaching, and element depletion processes proceed, the growing conditions in the soil for plants of all kinds become more stressful. Symptoms of the increased stress are diminished plant vigour, poor root development, slow growth, low resistance to pests and diseases, low yields, and declining nutritional value of the produce.

Modern agriculture’s use of conventional technology – employing large applications of inorganic or organic fertilisers, new plant varieties, a range of agricultural chemicals, and crop rotations – may overcome some of these stresses on a year to year basis. But many modern practices are, at best, expensive quick fixes. They fail to address the fundamental, longer-term problems of highly weathered and strongly leached soils that are, to all intents and purposes, worn-out.

With the current world population of 5.9 billion people (United Nations Statistical Papers, Oct 1997) set to expand to 8.3 billion by the year 2025 (United Nations World population Prospects 1995), agricultural production must increase dramatically to cater for the increasing demands for food, fibre, and materials for shelter. Agricultural production is being driven increasingly onto marginal land, especially in tropical regions where the population pressures are greatest. Highly weathered, acidic, infertile soils comprise some 15% of the world’s land surface (2,300 million ha), of which 150 million ha is arable and currently used for permanent crop

production (Uexkull and Mutert 1995). Some 8 million ha of these soils are located in Australia, principally in North Queensland (Craswell and Pushparajah 1989).

## 1.2 Chemical properties of highly weathered soils

Soils consist of gravel, sand, silt, and clay particles, often bound together in aggregates, with intervening pore spaces that hold the air and water which are essential for plant growth. Many of a plant's nutritional needs are met from nutrients dissolved in the water in the soil (the "soil solution"). These nutrients are present as positively charged "cations" or negatively charged "anions", just like the sodium cations  $[\text{Na}^+]$  and chloride anions  $[\text{Cl}^-]$  that are produced when table salt (sodium chloride) is dissolved in water.

In soils, the commonly occurring cations are calcium  $[\text{Ca}^{2+}]$ , magnesium  $[\text{Mg}^{2+}]$ , potassium  $[\text{K}^+]$ , and sodium  $[\text{Na}^+]$ , the "basic cations", and the first three are essential for growth in all plants. Hydrogen  $[\text{H}^+]$  and aluminium  $[\text{Al}^{3+}]$ , the "acidic cations", build up in highly weathered soils from which the basic cations have been lost by weathering and leaching. In the strongly acidic soils (those with a soil pH less than about 5.5), the aluminium cations may be concentrated to such an extent that they may become toxic, causing very poor growth in most plants, or even plant deaths. Only the most acid-tolerant plant species such as azalea, camellia, coffee, gardenia, rhododendron, and tea thrive on such soils.

Highly weathered soils are widespread in the humid tropics and are commonly found on land surfaces that have undergone extensive leaching as a consequence of their age, climatic setting, or both. The intensive weathering processes that the soils have undergone have resulted in the loss of many of the more mobile plant nutrients and a residual concentration of relatively immobile elements in the soil profile (e.g. iron and aluminium).

As a consequence, highly weathered soils display a range of properties detrimental to plant growth, including:

- lack of nutrient supplied from weatherable minerals (Aubert 1962),
- rapid oxidation of organic matter leading to degeneration of soil structure (Huges 1981),
- high rates of mineralisation (Greenland 1981),
- reduced levels of exchangeable basic cations (Juo 1981),
- strong soil acidity (Aubert 1962; Gillman 1987),
- low availability of, or high requirements for phosphorus (Fox *et al.* 1968; Juo and Fox 1977; Coleman *et al.* 1981; Edwards 1987),
- inability to respond to liming (Aubert 1962; Juo 1981; Gillman 1987),
- restricted micro-organism activity (Foy 1984),
- low levels of calcium and magnesium (Uehara and Gillman 1981).

To understand the way in which fertilisers and soil conditioners work in highly weathered soils, it is important to understand several fundamental characteristics of soils including: cation exchange reactions, soil acidity effects, and phosphate fixation processes.

### 1.2.1 Cation Exchange Reactions

The international chemical fertiliser industry was developed towards the end of the nineteenth century to overcome the plant nutrient deficiencies and imbalances, which were known to occur in the soils of the temperate regions of the world. As more attention began to focus on soils of the wet tropics late in the twentieth century it was realised that, after only limited cultivation and cropping, severe shortages of the major elements (nitrogen, phosphorus, potassium, calcium, and magnesium) became manifest in the soils. The ability of a soil to retain and supply nutrients as positively charged cations to plants (i.e. the "cation exchange capacity of the soil") was found to be controlled primarily by the composition and mineralogy of the soil constituents, particularly that of the clay fraction.

Many soil processes are driven by the electrochemical charge characteristics of the soil components. The strongly reactive components of the soil are the “colloids”, which are very tiny fragments of mineral or organic (humic) materials in the soil. They are finer than 2 thousandths of a millimetre ( $< 0.002$  mm) and present large surface areas in the soil upon which many chemical reactions take place. The surfaces of the colloidal particles usually carry a net negative electrical charge. To maintain a neutral electrical state in the soil, positively charged cations are attracted from the soil solution and are held loosely on the negatively charged sites on the surfaces of the colloids by electrostatic forces that operate similarly to the way iron filings may be held by a magnet. Different soil colloids have different abilities to attract and hold cations from the soil solution. The cations may swap, or “exchange” positions between the surfaces of the colloids and the soil solution depending on the mineralogical and chemical properties of the soil. The overall effect determines the “cation exchange capacity” (CEC) of the soil.

Soils with low cation exchange capacity are extremely common in the humid tropics of the world. Because of their chemical properties, such soils have low capacities to retain cations in the soil, only weak capacities to supply basic cations to growing plants, and are generally of low fertility.

Certain highly weathered tropical soils are at significant risk because their negative charge, hence their CEC, can be diminished very nearly to extinction by natural weathering processes and inappropriate land management practices (Gillman & Sinclair 1987). Consequently, the basic nutrient cations may be almost entirely leached from the soil by heavy rainfalls resulting in a marked decrease in soil fertility (Gillman & Bristow 1990), an increase in soil acidity, and increased environmental hazards in streams and coastal wetlands through the consequent enrichment of plant nutrients in the drainage waters.

## 1.2.2 Soil acidity

Hydrogen and aluminium ions, the “acidic cations”, may be held tightly on the surfaces of colloidal organic matter and clay minerals of highly weathered soils. The ability of the soil to release these particular ions to the soil solution is one measure of its acidity. The soil acidity level is a major control over the amount and kind of nutrients available in the soil to be taken up by plants during their growth.

Soil acidity is measured on a pH scale from 0 (extremely acid), through 7 (neutral), to 14 (extremely alkaline) and, although most plants prefer to grow in soils with a pH of 6.5 - 7.0, there are some that can tolerate more acid or more alkaline soil conditions. The pH of a soil influences the uptake by plants of nutrient ions from the surfaces of soil colloids or from the soil solution. Generally, plant growth is seriously diminished in the strongly acidic soils of the world through the build-up of toxic levels of aluminium and manganese. Plant growth is also strongly inhibited in highly alkaline soils, but these are somewhat rare in the humid tropics.

The pH of acidic soils can be raised by additions of lime [ $\text{CaCO}_3$ ] or dolomite [ $\text{CaMg}(\text{CO}_3)_2$ ] at rates of the order of 1.5 - 10 t/ha. Bruce (1988) and Cumming and Elliott (1991) described the main benefits of liming acid soils as:

- promoting plant growth by adjusting the soil pH to the range preferred by the specific crop;
- reducing the solubility, hence the toxicity, of aluminium and manganese in strongly acid soils (pH less than 5.5);
- providing a better plant response to fertiliser additions by increasing the availability of essential plant nutrients such as molybdenum;
- enhancing legume growth by providing a more suitable environment for microbiological activity that enhances plant growth.

Unfortunately, the beneficial effects of lime or dolomite applications are generally short-lived under the heavy soil leaching processes that prevail in the humid tropical conditions. The soils may consume large quantities of lime to raise the soil pH to an appropriate level, and the benefits are largely confined to the immediate topsoil (Cumming and Elliott 1991).

The major factor limiting plant growth of an estimated 56% of the land area of the humid tropics is aluminium toxicity (Sanchez 1987). Aluminium preferentially occupies exchange sites on the soil colloids as pH decreases. Below pH 5, aluminium is released from the soil surface and blocks a portion of the charge sites, excluding basic cations such as calcium (Gillman and Sumpter 1986b). For a given soil, an increase in aluminium saturation of exchange sites will result in a greater concentration of aluminium in the soil solution due to ionic equilibrium processes (Gillman *et al.* 1989). In a wide range of Queensland soils, Bruce (1988) found that the soil aluminium activity could be predicted by analysing the aluminium saturation of the exchange sites and the ionic strength of the soil solution.

An increase in soil pH also affects the concentration of soluble silicon in the soil solution. A number of soils found in the humid tropical regions have low soluble silicon contents, and low silica to sesquioxide ratios (Menzies 1991); their silicon concentrations in soil solution rise or fall in a direct relationship with soil pH (Jones and Handreck 1967). An increase in pH increases the soluble silicon content of the soil, which may promote plant health due to its incorporation into plant cell walls, therefore decreasing susceptibility of damage from wind and insect attack (Jones and Handreck 1967).

### 1.2.3 Phosphate fixation in soils

Phosphorus, an element that is essential for the adequate growth of all plants, is commonly available only in very low amounts in many soils of the humid tropics. While the amount of total phosphorus in the soil may be relatively high, the element may be in a form that is unavailable to plants (Singer and Munns 1992). The suite of clay minerals, and iron and aluminium oxides and oxyhydroxides associated with highly weathered soil systems have a major effect on phosphate sorption (Juo 1981). In neutral to acid soils, phosphate sorption is associated with aluminium and iron hydroxides, the edges of silicate clay minerals (Brady and Weil 1996), and also amorphous minerals (Singer and Munns 1992).

Phosphorus contents in the soil are commonly supplemented in Australian agriculture by the application of phosphatic fertilisers such as superphosphate, diammonium phosphate, or rock phosphate. The fertiliser dissolves in the soil under the action of rain or irrigation water, and its components will be held in the soil form that can be absorbed by plants. The phosphorus in the dissolved phosphate anions can form chemical bonds with the iron or aluminium atoms that form oxides or oxyhydroxides in highly weathered soils. This means that the phosphorus will then be locked onto the solid part of the soil, and will have effectively been removed from the soil solution. The phosphorus that was added in the fertiliser is then no longer available in the liquid phase, and cannot therefore be taken up by the plant roots. This is what is meant by “phosphate fixation”.

Uehara and Gillman (1981) have shown that soils containing the most amorphous oxide minerals and hydrous oxides of iron and aluminium absorb the largest amounts of phosphorus. Fixation reactions in acidic, iron-rich soils may allow only a small fraction (10 – 15%) of the phosphorus supplied in phosphatic fertilisers and manures to be taken up by plants in the year of application (Brady and Weil 1996). A major consequence of the widespread phosphate fixation problem in humid tropical soils is that the land manager does not gain the full agronomic benefit from the expensive fertiliser that has been applied to the soil. Consequently, there is a tendency for many managers to over-fertilise by applying additional fertiliser over the amount that stays in the soil solution and can be taken up by plants. Not only do the surplus fertiliser additions add unnecessary expense to the farming enterprise, but they may also be mobilised by erosion into the downstream parts of the ecosystem and contribute to nutrient enrichment in sensitive riparian or wetland environments.

The mechanism of sorption occurs by ligand exchange, a process in which hydrolysed phosphate anions are incorporated onto the surface of soil minerals by the replacement of a hydroxyl anion on the mineral surface with a hydroxyl ion from the hydrolysed phosphate (Singer and Munns 1992). Rajan and Fox (1975) concluded that at low concentrations of added phosphate, ligand exchange was associated with phosphate exchanges with sorbed water, sulfate, silicate and hydroxyl anions from metal hydrous oxides and the aluminium cations on the edges of clay mineral lattices.

At higher concentrations of phosphate added to a soil, phosphate sorption occurs by two additional mechanisms. Firstly, by competition with the hydroxyl ions linking aluminium atoms in the crystal lattices of mineral oxides or oxyhydroxides, which disorganises the crystal structure, thereby providing new sites for sorption. Secondly, by replacing the structural silicate anions in the clay colloid, thereby allowing more phosphate to be sorbed by the aluminium remaining in the clay.



The addition of a silicate-enriched soil conditioner, which provides silicate ions that compete for the exchange sites on the soil colloid, is expected to reduce the sorption of subsequent applications of phosphatic fertilisers (Uehara and Gillman, 1981, p. 81), thus increasing the availability of the applied phosphate for plant growth.

### 1.3 Use of rock dusts to improve soils

Deficiencies in essential elements in the soil may be addressed by the application of fertilisers, which are basically sources of plant nutrients, whose cycling is stimulated through the soil and the plant. The rock dust-based soil ameliorants of the present project are soil conditioners and modify the properties of soils, especially their cation exchange capacities, acidity, and phosphorus fixation capacities, such that water and plant nutrients are made more readily available to the growing plants. Soil conditioners do not necessarily provide nutrients to plants, but change the properties of soils such that fertilisers may work more efficiently.

In Australia, land managers have traditionally attempted to optimise their crop yields from humid tropical soils by using fertilisers and land management practices developed for temperate soils. Alternative methods of soil conditioning utilising nutrient elements from relatively fresh, unweathered rock-forming minerals may be more suitable for tropical soils. Tropical regions with high rainfall, young landscapes, and soils replenished by successive volcanic ash deposits such as parts of Indonesia and The Philippines have some of the most fertile soils in the world (Kronberg and Nesbitt 1981). Anthropogenic methods of renewing degraded mature or senile soils and landscapes with crushed rock materials are increasingly gaining recognition (Chesworth *et al.* 1983; Leonardos and Kronberg 1987). A fledgling industry using soil conditioners made from quarry waste materials or industrial wastes such as furnace slags is beginning to emerge around the world (Campe 1996).

Land managers seek to rectify the low availability of nutrients by adding soil amendments such as fertilisers, or by increasing soil pH with lime. Liming is uneconomic in many situations due to the dominating influences of the aluminium and iron oxides in the clay fraction of highly weathered soil systems. The effect of mineralogy of several weathered tropical soils on their lime requirement was investigated by Gillman and Sumpter (1986b), who reported that soils from granitic and metamorphic parent materials needed lime equivalent to the exchangeable aluminium content. They found, however, that soils from basaltic parent materials required a lime application equivalent to 2 to 3 times that of the amount of exchangeable aluminium in the soil solution. The limitations of traditional liming materials due to their effective life span in tropical regions of high rain fall has prompted research into the use of silicate-based amendments such as crushed basalt to sustain agricultural production in the tropical regions of the world.

#### 1.3.1 International research

Some 75 years ago, McGeorge (1924) carried out pot trials on sugarcane growing in basaltic soils of Hawaii and found that higher soluble silica contents in the soil increased the availability of phosphorus to the cane, and that the sucrose obtained from the cane also had higher phosphorus contents. Sodium silicate was applied to pot trials using Sudan grass as an indicator plant on two basaltic soils with mixed results reported by Sherman *et al.* (1955). When sodium silicate was applied at a rate of 900 kg / ha, one soil showed no response to the amendment whereas the other showed a 3-fold increase in yield, and the disappearance of foliar symptoms of phosphorus deficiency. Sodium silicate was also used in Hawaiian soils by Ikawa (1956) who found a reduction in phosphorus fixation and a significant increase in sugarcane growth rates and dry matter yields.

Similar positive results from using silicate-based soil conditioners and re-mineralising agents have been known for more than 60 years from studies of sugarcane growth on the island of Mauritius, but the research results have not been applied in Australian agriculture. It is well worth studying the report of one of the original researchers, O. d'Hotman de Villiers (1961), who wrote:

*"It is now 25 years since the writer, from the classical studies of N. CRAIG and P. HALAIS on the soils of Mauritius at the Sugar Cane Research Station as well as his own work on the soils of Highlands S.E. and annexes carried out at the same Institution, concluded that the extremely impoverished free soils of the superhumid regions of the island, which were giving mediocre responses to liberal doses of N.P.K., could be rejuvenated by application of adequate quantities of crushed basalt, the mother rock from which almost all the soils of the Colony are derived."*

... The first open field experiments with crushed basalt laid out on approved statistical lines ... were planted in 1938 at Hermitage (Belle Rive) where the annual rainfall is about 135 inches [3430 mm] so that the soil there is the totally leached out, acid residuum composed mainly of hydrous oxides of iron, aluminium and titanium, with comparatively very little silica.

The results of all these carefully conducted trials with doses of basalt from 10 to 90 tons per acre [22 – 202 t/ha, showed] ... that crushed basalt conclusively proved its capacity for very significantly increasing cane yields of [varieties] POJ 100, M27/16, and M134/32 under heavy or normal fertilization with N.P.K. In other words, the response of the basalted soil to chemical fertilization, using the current salts with phosphatic guano, had been very significantly increased. In addition, the writer obtained a significantly positive effect of increasing doses of crushed basalt on juice quality in several instances and this, it can be stated today, was strikingly corroborated by a six-year experiment in large pots with POJ 2878 and Co. 301.

... the writer left the colony but S.M. FEILLAFE, also of the Station, took over the matter ... and, every year, published in the Annual Reports the results of another carefully conducted field trial ... the notably greater response of the basalted soil to the fertilizers applied, predicted by the writer since 1937, is once more very evident.

... In 1955 the Institution laid out a new field experiment at Rose Belle (Cascade) for measuring the effect of four levels of crushed basalt, viz: none, 45, 90, and 180 tons per acre, [0, 101, 202, and 404 t/ha] once again under heavy fertilization and, furthermore, with the variety B3337 which, like POJ 100 used by the author in his very first Latin Squares, [experiment] is adapted to poor soils. Here are the results ...

	<i>tons per acre</i>			
<b>Basalt applied</b>	<b>0</b>	<b>45</b>	<b>90</b>	<b>180</b>
<i>Plant cane</i>	15.5	23.1	27.9	31.1
<i>1<sup>st</sup> Ratoon</i>	39.2	44.8	47.1	49.6
<i>2<sup>nd</sup> Ratoon</i>	32.7	36.9	37.9	36.5
<i>3<sup>rd</sup> Ratoon</i>	37.3	39.7	41.2	44.0
<b>Total gain in four crops</b>		<b>19.8</b>	<b>29.4</b>	<b>36.5</b>

The writer could not desire more powerful experimental evidence of his thesis and predictions. Such a demonstration, as well as all the other statistically significant results accumulated during the past two decades, are not only of the highest interest to agricultural science, but they evidently are of practical value, especially on a small island where a rapidly growing population is causing the gravest concern to the authorities. Whether the effect of basalt in the soil is physical or chemical or both, would be immaterial to the economist to whom the substantial gains in yield, repeatedly obtained for years, is all that really counts; provided the preparation, transport and application of the rock dust are not prohibitively expensive."

Parish and Feillafe (1958) reviewed the previous research reports of Feillafe (1950, 1952) and showed that major improvements in sugarcane yields resulted from applications of between 100 t/ha and 400 t/ha of crushed basalt to the poor, highly weathered soils of Mauritius; significant increases in sugarcane tonnages and sucrose contents were still evident 8 years later.

Leonardos *et al.* (1987) conducted field trials in Brazil on the growth responses of eucalypt trees growing in highly weathered, humid tropical soils to which had been added combinations of N, P, K fertilisers and crushed basalt; they were compared with controls to which no treatments had been applied. After 6 years, trunk diameters were greatest in the trees grown on the soils to which had been applied fertiliser and crushed basalt.

Trees grown in soils treated with basalt alone had larger trunk diameters than those grown in the soils to which only the fertilisers had been added. All the trees grown on amended soils were larger than the controls grown with no treatments at all.

Other silicate-based soil conditioners, such as Portland cement (a mixture of calcium silicates and calcium aluminates), may also be used to modify the properties, and thereby improve the productivity of highly weathered tropical soils. For example, Wong You Cheong and Halais (1970) compared the effects of applications of lime and Portland cement on sugarcane soils in Mauritius; although both treatments had similar beneficial effects on soil acidity, the cement treatment produced a significantly larger increase in crop yield. From this, they concluded that sugarcane had a basic requirement for silicon.

In Hawaii, Ayres (1966) compared the efficiency of using crushed limestone and calcium silicate slags from electric and blast furnaces, at equivalent calcium application rates, as growth stimulants for sugarcane on several soils with low silicon contents. The slag provided highly significant increases in plant growth, but the limestone was found to have no effect on plant growth unless the soil was specifically calcium deficient. Ayres (1966) also found that silicon levels in the soil and sugarcane tissues were dramatically increased by the slag treatments. He concluded that, “there is a level of extractable, or available, soil Si below which satisfactory growth of sugarcane will not result, regardless of the supplies of macro- and micronutrients available to it. When compensation is made for this Si deficiency through addition of reactive silicates to the soil, optimum yields may be achieved.”

Calcium silicate slag, a by-product from manufacturing steel, was also trialed in Hawaii in 1965–66 by Fox *et al.* (1967, 1969), and plant vigour and yield increased consistently with increased application rates up to the maximum rate applied (8t/ha). The dominant effects noted were an increase in plant silicon and calcium contents, and a decrease in plant manganese content. Similar positive responses to silicate amendments, generally derived from fly ash or crushed furnace slags, have been observed in sugarcane crops in Hawaii (Clements 1965; Plucknett 1972) and Florida (Gascho 1978). Similarly, Silva (1971), Datnoff *et al.* (1999), and Korndörfer (1999) have discussed some of the possible mechanisms for improved crop growth responses to silicate applications over a variety of soils and climates.

In soil-free, nutrient solution trials, Wong You Cheong *et al.* (1973) studied the effect of silicic acid on sugarcane growth in a pure nutrient solution; they reported an increase in stalk and root weight and the absence of leaf freckling on treatments receiving silicic acid. In other soil-free trials, Barcelo *et al.* (1993) and Epstein (1994, 1999) found enhanced plant growth responses through the action of silicon in ameliorating the toxic effects of high aluminium in acidic growing media.

### 1.3.2 Previous Australian studies

Although a few studies have been made in Australia using silicate-based soil conditioners such as calcium silicate slags or Portland cement, very little research has been undertaken in this country into the effectiveness of rock dusts to improve plant growth.

#### *Studies in temperate Australia*

Investigators in temperate Australia are beginning to study the complex interactions that occur when rock dust is added to the soil (Zdrilic and Dumitru 2000). The type of rock dust, the nature of the soil to which the dust is applied, and rates of weathering and mineral breakdown are extremely important factors in the effective use of rock dusts (Harley 2000).

Harley and Gilkes (2000) recommended the use of rock dust as a slow release fertiliser for several reasons, including:

- it is not readily leached from the soil,
- it is acceptable to ‘organic’ farmers,
- it is affordable in developing countries,
- it can reduce stockpiles of quarry or mining by-products.

Acidic soils were thought to be the most receptive for the application of rock dust because such soils can release cations rapidly from the rock dust, which soils with neutral pH cannot (Harley and Gilkes 2000). Because mineral dissolution is governed by temperature and precipitation, the application of rock dust is probably most

effective in humid, warm environments, where there are often also old, highly weathered soils which lack the nutrients the rock dust can release (Harley and Gilkes 2000).

Bolland and Baker (2000), however, were strong in their criticism of the use of granitic rock dusts as a slow-release fertilisers in sandy soils of Western Australia; they went so far as to suggest that there was so little potassium benefit to be obtained that the quarry managers should pay farmers to take away the rock dust!

#### *Studies in tropical Australia*

Hurney (1973) carried out a series of pot trials using soils from south-east Queensland, and field trials established in the Cairns-Innisfail area using Portland cement as a source of calcium metasilicate. He demonstrated that growth responses to silicate material could be achieved on 7 of the 10 soils tested. The 3 non-responsive soils all lay outside the humid tropic region and were found to have natural silicate materials available in a water soluble form, which offset the effect of the applied silicate compound.

Haysom and Chapman (1975) conducted field trials with a calcium silicate soil conditioner on 5 soil types at Mackay, north Queensland (brown podzolic soil, 2 solodic soils, a grey brown podzolic soil, and a soloth). They found that the soil conditioner led to increased cane biomass on all the treated soils.

In an unpublished laboratory study, a crushed basaltic scoria containing 21% silicon, 7% magnesium, 7% calcium, 1% potassium, and 8% iron was applied by G.P. Gillman (pers. comm.) to a red basaltic soil and a yellow alluvial soil (the Pin Gin and Tully Soil Series of Murtha 1986, respectively) from the humid tropical Innisfail area, north Queensland. After an incubation period of 18 months, both soils showed an increase in pH, as well as increases in exchangeable calcium and magnesium contents. Another pot trial was carried out using the same soil conditioner (at rates of 0, 50, 100, 150, and 200 t/ha) with the same soil types and 2 indicator plants (a legume, *Stylosanthes*; and a grass, *Panicum*). Gillman's unpublished results showed that the silicate-based soil conditioner provided no benefit to the legume, and was detrimental to its growth at amendment application rates of 50 t/ha and higher. However, the grass showed a dramatic response to all application rates of the soil conditioner.

In another laboratory study, Gillman (1980) applied crushed basaltic scoria to samples of a red basaltic soil obtained from near Innisfail, north Queensland. The scoria was crushed to 3 degrees of fineness, applied at rates of 100, 200, and 300 t/ha, and incubated for periods up to 12 months. Gillman (1980) found that the soil pH increased from 5.4 to 6.9, the cation exchange capacity increased from 6.4 meq% to 14 meq%, and the contents of exchangeable cations (calcium, magnesium, and potassium) had doubled with increasing application rates of the silicate-based amendment, its degree of fineness, and the duration of the soil incubation period. He concluded that, "*a single large application of the basalt cinders may obviate the need to apply Ca and Mg for many years, as well as reduce the leaching losses of applied  $NH_4$  and K [ammonium and potassium] over a similarly long period*" (Gillman 1980).

Dr Gavin P. Gillman and co-researchers have addressed themes of major significance to the use of basalt-derived, silicate-based soil conditioners in sustaining agricultural production in the humid tropics. Their results are set out in a series of publications, including:

- the exchangeable cation status of tropical soils (Gillman and Bell 1978; Uehara and Gillman 1981; Gillman *et al.* 1982; Gillman *et al.* 1983; Gillman and Sumpter 1986a; Gillman and Yu 1986),
- the maintenance of soil fertility (Gillman 1985; Toreu *et al.* 1988; Gillman *et al.* 1989; Oades *et al.* 1989),
- soil surface charge characteristics (Gillman 1984; Gillman and Sumner 1987),
- soil acidification and lime requirements (Gillman and Sumpter 1986b; Gillman 1987; Gillman and Bristow 1990),
- grouping of soils with similar charge properties (Gillman and Abel 1986; Gillman and Sinclair 1987),
- leaching of nutrients from tropical soils (Gillman *et al.* 1989).

These studies have provided part of the scientific framework for the present project.

### 1.3.3 Minplus™: a silicate-based soil conditioner

Our Industry Partner, *Pacific Mineral Developments Pty Ltd*, Innisfail, has manufactured a finely crushed, silicate-based rock dust for almost a decade. It has been marketed as “*Minplus™*” and consists predominantly of calcium and magnesium silicates.

Derived from the fine, non-commercial products of a rock quarry, the very finely crushed basaltic rock (particle size less than 250  $\mu$ m) is known to be able to raise soil pH, improve the negative charge in the soil, and deliver balanced quantities of calcium, magnesium, and a range of other essential plant nutrients, in ionic forms to occupy the increased negatively charged sites in the soil. The material is approximately 60% silicate anions, the bonding of which to oxidic sites on soil particles also increases negative charge, but in a more permanent way than by the reversible process of increasing soil pH. The large amounts of silicate anions can also reduce “phosphate fixation” in those soils where it is a problem.

Over the past 5 - 8 years, Pacific Mineral Developments Pty Ltd has established a market for Minplus™ of about 2000 t/year, the bulk of which is supplied to landholders in the Innisfail region. There is a small, but growing international market in the USA, Europe, South East Asia, and the Middle East.

A large number of the users of Minplus™ have found significant improvements in crop production that they have attributed to the beneficial effects of Minplus™. Only few of those results have been published to date (Campe 1993; Edwards 1993). The anecdotal evidence includes:

- faster plant growth,
- hardier plant foliage,
- greater plant resistance to pests and diseases,
- increased friability of the soil,
- bigger, stronger, and healthier-looking roots of tree crops,
- reduced stool tipping in bananas during cyclonic winds,
- more vigorous soil animal populations,
- increased capacity of the soil to retain, in the root zone of the plants, moisture and nutrients applied as fertilisers,
- improved crop yields and produce quality.

Although the land managers have not understood why such changes have occurred in their soils and crops, many have been sufficiently impressed with the performance of Minplus™ in the soils of the humid tropics that they have made repeat orders for the product over a number of years. Hence, before our research began, it was known that certain plants would respond to Minplus™ applications over particular soils in the humid tropical Tully – Innisfail area (Fig. 1.1). The research is providing an understanding of the soil and plant processes involved.

**Figure 1.1**

The coastal lowlands of north Queensland to which the results of the present study are particularly relevant. Source: Murtha and Smith (1992).

Detailed soil mapping information is available for the region from the following CSIRO Division of Soils, Divisional Reports:

- Cardwell – Tully: No. 115,
- Tully – Innisfail: No. 82,
- Babinda – Cairns: No. 123,
- Mossman – Cape Tribulation: No. 102



## 1.4 Research strategy

Qualitative improvements in crop yields by amending soils with crushed basalt have been commonly observed (Campe 1996). Nevertheless, few observations have been quantified. Improved crop yields may occur by mechanisms such as increasing soil pH, soil cation exchange capacity, and available cations, or by reducing phosphate fixation. More knowledge is required to provide a better understanding of the operative mechanisms.

The ability of crushed basalt to supply nutritional benefits to highly weathered soils depends partly on the particle size of the amendment. While some research reports into crushed rock amendments have neglected to mention their particle sizes at all, others have defined the particles qualitatively on the basis of 'fine', 'medium', and 'coarse' (e.g. Leonardos *et al.* 1987). It is generally recognised that finely crushed particles are more beneficial than coarser particles (McSkimming 1998). But little is known, however, about the optimum particle size and where the economic cut-off for the energy-intensive and costly grinding process lies.

The intrinsic ability of crushed basalt to increase soil fertility is dependent on the specific mineralogical composition of the source rock. Identification of the 'active ingredients' in terms of having the potential to provide nutrients, increase the soil cation exchange capacity, increase soil pH, and reduce phosphate sorption will ensure that the most effective rocks are utilised. Furthermore, possible agronomic benefits occurring as a consequence of amending soils with crushed rock dusts, such as improving soil moisture properties or increasing microbiological activity in the soil, need to be addressed.

The range of essential plant nutrients that crushed basalt is able to supply is fixed by its chemical composition. Basalt lacks nitrogen, is grossly deficient in sulphur, and contains relatively low contents of phosphorus and potassium. Investigations are required into supplementary sources of these nutrients that will satisfactorily combine with crushed basalt to form an improved soil conditioner.

Soils vary tremendously in their physical, chemical, and biological properties. Extensive field trials need to be conducted to determine which soils receive benefits from soil conditioners made from crushed basalt, and which ones are less responsive. Similarly, different plants are likely to respond to crushed basalt soil conditioners in different ways, and on different soils. Hence, crop responses also need to be characterised.

The present project has focused on the soils and plants of the humid tropical lowlands of north Queensland, with particular emphasis on the higher rainfall zone of the Tully – Innisfail area (Fig. 1.1). The research is thought to have applications to the acidic, highly weathered soils of other regions in Australia and throughout the world. Testing of our hypotheses across a wider region is dependent on the availability of funds to support such research.

### 1.4.1 Aims of the project

No Australian studies had addressed the practical issues raised by the use of silicate-based soil conditioners in humid tropical soils until 1997 when the present research program was initiated. The research program is built on the principles and approaches advocated by Dr G.P. Gillman and co-workers (Section 1.3.2, above), and is focussed on the 3 main areas listed below:

#### *Mineralogy and properties of Minplus<sup>TM</sup> rock dust*

Laboratory research to determine:

- the mineralogy and chemical composition of quarry products used to manufacture Minplus<sup>TM</sup>,
- the most effective size of grinding of the rock dust to maximise the soil conditioning effect of Minplus<sup>TM</sup>,
- the potential for incorporating crushed natural geological products (e.g. potassium-rich granite, gypsum, or rock phosphate) as potassium, sulphur, or phosphorus supplements during the manufacturing of Minplus<sup>TM</sup>;
- the effectiveness of Minplus<sup>TM</sup> in supplying nutrients to plants.

#### *Properties of Minplus<sup>TM</sup>-treated soils*

- Laboratory, shadehouse, and field trials to determine:
- the mineralogy and chemical composition of a range of soils both before and after amelioration using Minplus<sup>TM</sup> rock dust;
- the range of soil types over which the silicate-based soil conditioners may be effective;
- the ability of highly weathered tropical soils to retain nutrients after Minplus<sup>TM</sup> applications;
- the length of time over which Minplus<sup>TM</sup>-induced improvements in soil chemical properties might be expected to persist in a variety of strongly leached soils under heavy seasonal rainfalls.

#### *Plant nutritional responses to soil conditioning*

Laboratory, shadehouse, and field trials to:

- determine the growth responses of a range of tropical crop and pasture plants to applications of Minplus<sup>TM</sup> and other amendments (e.g. lime, cement) in specific soils;
- establish the most effective methods for using Minplus<sup>TM</sup> in combination with conventional N-P-K fertilisers to ensure optimal plant growth in highly weathered tropical soils;
- compare plant growth responses to Minplus<sup>TM</sup> treatments (calcium and magnesium silicates) with responses to liming (calcium carbonate) and cement (calcium silicate and calcium aluminate) treatments.

## 1.4.2 Potential research benefits

Application of the research results will provide benefits to agricultural production and environmental protection in the humid tropics of Australia and elsewhere in the world from the use of Minplus™ as a soil conditioner through:

- improved plant growth in acidic, highly weathered soils with low cation exchange capacities and low inherent fertility;
- farming strategies to ensure more sustainable uses of soil resources and fertilisers;
- reduced fertiliser use, especially in soils with strong phosphate fixing properties;
- import replacement as a result of diminished use of high-cost imported fertilisers;
- environmental benefits from decreased nutrient losses from farmlands;
- reduced nutrient enrichment in sensitive natural wetlands and nearshore marine systems.

## 1.4.3 Research activities

Much of the hands-on components of our research has been carried out by BSc Honours and Masters level students. Their research tasks have been conceived, carried out, written up, and completed in the School of Tropical Biology at James Cook University under the supervision of Dr Coventry, or under joint supervision with Dr Gillman or other University staff members.

Research student activities supported by RIRDC Project UJC-4A are listed in Table 1.1; other activities closely related to the present project, but not supported financially by it, are listed in Table 1.2. Details of individual research activities are presented in the following Chapters of this report.

### *Research papers published to date*

Gillman, GP, Burkett, DC, and Coventry, RJ (2001). Application of basalt dust to highly weathered soils. *Australian Journal of Soil Research*, **39**, 799-811.

### *Conference presentations to date*

Gillman, GP, Burkett, DC, and Coventry RJ (2000). Amending highly weathered soils with finely ground basalt rock. *International Symposium on Environmental Geochemistry*, 24 – 29 April 2000, University of Cape Town, Cape Town, South Africa.

Gillman, GP, Burkett, DC, and Coventry RJ (2000). Amending highly weathered soils with finely ground basalt rock. *Environmental geochemistry of soils*, Soil Science Society of America, April 2000, University of Indiana, Bloomington, Indiana, USA.

Burton, ME (2001).

The effects of volcanic rock dust (Minplus™) on soil chemical properties and plant growth in the humid tropics, north Queensland. *GEOTROP 2001, 4<sup>th</sup> International Conference on Environmental Chemistry and Geochemistry in the Tropics*, 7-11 May, 2001, Townsville, Australia.

### *Theses and dissertations*

Eleven unpublished theses and dissertations have been prepared by students at James Cook University on topics arising from the present project. They have been submitted in partial fulfilment of requirements for various research degrees and are listed in Tables 1.1 and 1.2.



Table 1.1 Summary of research student activities directly supported by RIRDC Project UJC-4A.

RESEARCHER	RESEARCH PROJECT Title, focus, and supervisors	RIRDC SUPPORT PROVIDED	ACADEMIC RESULT
<b>Dennis Burkett 1997 – 1999</b>	<p><i>Rejuvenation of highly weathered soils using silicate-based amendments.</i></p> <p><b>Soil chemistry:</b> soil chemical properties and leaching studies on 7 soils from the Tully-Innisfail area: Tyson, Tully, Pin Gin, Mundoo, Innisfail, Galmara, Kurrimine Series Soils as described by Murtha (1986).</p> <p><b>Supervisors:</b> G.P. Gillman and R.J. Coventry</p>	Stipend (\$18,000/year) + operating funds	Master of Applied Science
<b>David McSkimming 1998</b>	<p><i>The potential of crushed basalt to ameliorate humid tropical soils.</i></p> <p><b>Mineralogy and geochemistry:</b> properties of Minplus™ and potential additives</p> <p><b>Supervisor:</b> R.J. Coventry</p>	\$6,770 (HECS & living allowance) + operating funds	BSc with First Class Honours
<b>Michelle Smallwood 1998</b>	<p><i>Rejuvenation of a highly weathered tropical soil with the silicate-based soil amendment Minplus™</i></p> <p><b>Plant nutrition:</b> Pin Gin Series Soil – pot trials</p> <p><b>Supervisors:</b> R.J. Coventry, G.P. Gillman, and E. Guyris</p>	Some operating funds only	BAppSc Honours, Level 2A
<b>Therese Brown 1998</b>	<p><i>Plant responses to a crushed basaltic soil amendment in highly weathered tropical soils</i></p> <p><b>Plant nutrition:</b> Tully and Innisfail Series Soils – pot trials</p> <p><b>Supervisors:</b> R.J. Coventry, G.P. Gillman, and R.A. Congdon</p>	\$6,770 (HECS & living allowance) + operating funds	BSc Honours, Level 2B
<b>Margaret Burton 1999</b>	<p><i>The effects of volcanic rock dust (Minplus™) on soil chemical properties and plant growth in the humid tropics, north Queensland</i></p> <p><b>Soil chemistry and plant nutrition:</b> Innisfail Series Soil – pot and field trials</p> <p><b>Supervisors:</b> R.J. Coventry and P.F. Brownell</p>	\$6,770 (HECS & living allowance) + operating funds	BSc Honours, Level 2A
<b>Francisco Jacintho 1977 – 1999</b>	<p><i>Rejuvenation of a tropical pasture using legumes, volcanic rock dust, and phosphatic fertilisers</i></p> <p><b>Plant nutrition:</b> Innisfail Series Soil – field trials</p> <p><b>Supervisors:</b> R.J. Coventry and C.P. Gardiner</p>	Some operating funds only	Master of Applied Science (in progress)

Table 1.2 Research activities closely related to, but not funded by RIRDC Project UJC-4A

RESEARCHER	RESEARCH PROJECT Title, focus, and supervisors	ACADEMIC RESULT
<b>Luxmei de Silva 1999 – 2002</b>	<p><i>The effect of soil amendments on chemical and microbial properties of tea soils in the humid tropics</i></p> <p><b>Soil chemistry, microbiology, and plant nutrition:</b> Pin Gin Series Soil – pot trials</p> <p><b>Supervisors:</b> R.J. Coventry and J.A. Holt</p>	PhD (in progress)
<b>Nicole Horner 1999 – 2000</b>	<p><i>The role of silicate-based soil amendments in establishing native grasses at the Cape Flattery Silica Sand Mine, north Queensland</i></p> <p><b>Soil chemistry and plant nutrition:</b> Nutrient-deficient silica sand - pot trials</p> <p><b>Supervisors:</b> R.J. Coventry, W. Edwards, and B.R. Jackes</p>	BSc Honours, Level 2B
<b>Margaret Burton 2000 – 2003</b>	<p><i>Sustaining agricultural production in the humid tropics: improved fertiliser use efficiency and reduced environmental impacts.</i></p> <p><b>Soil chemistry and plant nutrition:</b> Innisfail and Pin Gin Series Soils - field and pot trials</p> <p><b>Supervisors:</b> R.J. Coventry , P.F. Brownell, and D.C. Pollock</p>	PhD (in progress)
<b>Milagrina Pomares 2000 - 2001</b>	<p><i>Techniques for establishing shrub legumes in a vigorously growing tropical grass pasture</i></p> <p><b>Plant nutrition:</b> Innisfail Series Soil - field trial</p> <p><b>Supervisors:</b> R.J. Coventry and C.P. Gardiner</p>	MSc (in progress)
<b>Ramon Satimbre 2000 - 2001</b>	<p><i>Role of volcanic rock dust in improving the growth of vegetables in tropical soils</i></p> <p><b>Soil chemistry and plant nutrition:</b> Innisfail Series Soil, Pin Gin Series Soil, and 2 soils from the James Cook University campus; pot trials</p> <p><b>Supervisors:</b> R.J. Coventry, P.F. Brownell, and M. Johnston</p>	Master of Applied Science (in progress)

## 2. Properties of Minplus™ rock-dust

### 2.1 Mineralogy and geochemistry

#### 2.1.1 Minplus™ parent rocks

Minplus™ is produced from basalt from the Fishers Creek Quarry, which is located some 2 km north of the Palmerston Highway and approximately 12 km west of Innisfail, north Queensland. The quarry lies about 40 m above sea level at a longitude of 145° 55' E and latitude of 17° 33' S. The quarry produces aggregate from the basalt, which is graded into a variety of sizes for use in the construction of roads, railways, and concrete. Material too fine for use as a construction aggregate (finer than 7 mm) is collected from below the sieves at the jaw crusher in the quarry. It is used as the 'feedstock' for the ball mill where it is crushed to a powder. It is sold for agricultural purposes in 2 size classes: 'Minplus™ 250', which is the standard product, and 'Minplus™ 40', which is a superfine product; the products have particle-sizes nominally finer than 250  $\mu$ m and 40  $\mu$ m, respectively.

#### 2.1.2 Lithology and mineralogy of the Fishers Creek Basalt

The basalt *in situ* has a uniformly dark grey, unaltered appearance and hand specimens from the quarry show little variation. Olivine xenocrysts up to 20 mm long are sparsely distributed throughout. The rock is moderately vesicular, with partial infilling of voids by blue, black, green, or white clays. The major elements of 10 samples of the feedstock were analysed by X-ray fluorescence spectrometry at the Advanced Analytical Centre, James Cook University (Table 2.1). The low standard errors indicate that there is little variation in the bulk chemistry of the feedstock material collected from the jaw crusher residues in the quarry.

Orientated thin sections were prepared from rock samples for optical examination using a polarising microscope. Two carbon-coated polished thin sections were made from representative rock specimens for elemental analysis of minerals by electron microprobe in the Advanced Analytical Centre, James Cook University.

The basalt has a finely crystalline groundmass containing phenocrysts and xenocrysts and a connected network of extremely abundant, interstitial, non-crystalline, glassy material. The primary basalt mineralogy is uniform throughout all the samples and, with the exception of olivine and the volcanic glass, is well preserved (Table 2.2). Olivine and glass have inconsistently altered to secondary minerals at different locations due to the effects of weathering. The volcanic glass has been altered predominantly by hydration at the top of the quarry face, and by hydration near the quarry floor where the matrix has crystallised forming illitic and smectitic clays. Occasional thin veins infilled by clay minerals are located randomly throughout the rock. Vesicles are common, some infilled by zeolites and chlorites. More specific details of the mineralogy of the rocks are given by McSkimming (1998).

**Table 2.1** Average major element composition of Fishers Creek Basalt determined by X-ray fluorescence spectrometry of 10 feedstock samples. Source: McSkimming (1998).

Composition expressed as oxides			Composition expressed as elements	
Oxide	Average composition %	Standard error	Element	Average composition ppm **
SiO <sub>2</sub>	43.12	0.09	Silicon	216,000
Fe <sub>2</sub> O <sub>3</sub> *	12.82	0.06	Iron	105,000
Al <sub>2</sub> O <sub>3</sub>	12.68	0.10	Aluminium	76,000
MgO	11.18	0.22	Calcium	65,400
CaO	8.86	0.15	Magnesium	64,400
Na <sub>2</sub> O	2.28	0.05	Sodium	20,300
TiO <sub>2</sub>	2.21	0.03	Titanium	15,200
K <sub>2</sub> O	1.71	0.02	Potassium	12,500
P <sub>2</sub> O <sub>5</sub>	0.70	0.01	Phosphorus	3,030
MnO	0.18	0.00	Sulphur	2,150
SO <sub>2</sub>	0.00	0.00		
Loss on ignition				
**	<u>4.32</u>	0.24		
Sum	100.08			

\* Total iron, FeO and Fe<sub>2</sub>O<sub>3</sub> expressed as Fe<sub>2</sub>O<sub>3</sub>.

\*\* Loss on ignition accounts for water loss and oxidation during analysis at the Advanced Analytical Centre, James Cook University.

++ ppm = parts per million. (Note that 10,000 parts per million = 1 %).

**Table 2.2** Proportions of primary rock-forming minerals in the Fishers Creek Basalt as determined by visual estimation based on 16 thin sections. The relative proportions of the main plant nutrients derived from the minerals are also indicated. Source: McSkimming (1998).

Mineral	Abundance (area % of the rock)	Main plant nutrients available
Altered glass	37	Some Ca, Mg, K, P
Augite	30	16% Ca, 7% Mg
Plagioclase feldspar	12	8% Ca, 0.5% K
Magnetite	10	Abundant Fe, 2% Mg
Olivine	10	20% Mg, some Fe
Apatite	0.5	38% Ca, 17% P
Orthoclase feldspar	< 0.5	Minor K

## 2.2 Exchangeable cations

The ability of minerals to absorb or desorb nutrient cations is determined by their surface charge characteristics (van Olphen 1977). Negative surface charges loosely bond cations in solution, which are considered 'exchangeable' if they can be replaced by other cations in solution. The exchange sites may be occupied by the basic cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>, Na<sup>+</sup>) which are a prime source of essential plant nutrients. The sites may also be occupied by H<sup>+</sup>, Al<sup>3+</sup>, Fe<sup>3+</sup>, or other non-nutrient cations. The cations in the soil solution are concentrated in a diffuse layer in the solution close to the particle surface; their number in the diffuse layer is determined by the

size of the negative charge on the colloid surface and by the charge (i.e. the valency) and number of the positively charged cations in the soil solution.

The cation exchange capacity of the soil is a measure of the ability of the soil to retain cations on the colloid surfaces, and to supply them to the soil solution for uptake by plants (McBride 1994). The cation exchange capacity of the soil increases with the number of fine particles in the soil, the composition of the soil colloids, and the fineness of the colloids. Hence, the cation exchange capacity of a soil provides a measure of its potential to increase the fertility of the soil by acting as a store and source of nutrient cations (Troeh and Thompson 1993).

Two distinctly different mechanisms of charge can develop on crushed basaltic mineral surfaces, resulting in two different types of charge in the soil: variable charge surfaces, and permanent charge surfaces.

## 2.2.1 Variable charge surfaces

The surfaces of silicate minerals (olivine, augite, plagioclase) and oxide minerals (magnetite) have different atomic bonding structures from those inside the crystal lattices of the minerals. The abrupt boundary defining the surfaces of the minerals causes irregularities in the crystal structures at those surfaces, creating incompletely bonded O, Si, Al, Fe, and metal cations in the silicate minerals, or incompletely bonded O and Fe in magnetite. Strong negative or positive charges are imparted to the mineral's surface due to unpaired electrons trapped on the incompletely bonded, charged atoms at the surface of the mineral (Sposito 1990). By crushing the basalt, the crystal structures are broken which generates incompletely bonded charged atoms on the crystal surface (Parks 1990).

Highly reactive fracture surfaces on crushed minerals rapidly attract any available ions in an attempt to neutralise the high positive or negative surface charges. Reorganisation of the crystal surfaces may dislocate cations from surface sites into positions of charge balance (Parks 1990). When the charged, fractured surface encounters water, the high charge gradient causes an increase in the dissociation constant of water that is near the charged mineral surface relative to that of the bulk water (Stumm 1986). Under such circumstances, water rapidly dissociates:



The  $\text{OH}^-$  anions bond with incompletely bonded, positively charged atoms (cations), and the  $\text{H}^+$  cations bond with O atoms, producing surface hydroxide functional groups taking the form  $\text{MOH}$ , where M refers to a cation at a surface site of the solid mineral structure (Lasaga 1995). Additionally, cations previously balancing charge on mineral surfaces are rapidly replaced by  $\text{H}^+$  and lost to the soil solution (Loughnan 1969).

Like the primary basalt-forming minerals, hydrated basaltic glass also has an extensively hydroxylated surface (Casey and Bunker 1990). The extent of the hydroxylated surface is much greater, however, than that of the crystalline minerals because of the very extensive internal surface generated by its high microporosity (Furrer and Stumm 1986). The structure of volcanic glass has developed during its formation as incomplete cross-linking of coalesced hydroxy polymer strands forming interconnected structural voids with diameters typically less than 2 nm, creating a large 'internal surface' (Davis and Kent 1990).

Hydroxylated surfaces create charge by ionisation of the  $\text{MOH}$  functional sites (Parks 1990). The polarity and potential of the charge is controlled by the pH of the ambient solution (Uehara and Gillman 1981). Charge is derived from the adsorption or desorption of the potential-determining ions,  $\text{H}^+$  or  $\text{OH}^-$  from solution, depending on their availability, which is a function of the pH of the solution. At a critical pH, the net surface charge on the mineral surfaces reaches a condition of net neutrality, termed the 'zero point of charge' (PZNC), whereby positive charge is equal to negative charge (Casey and Ludwig 1995).

In alkaline solutions with pH greater than  $\text{pH}_{\text{PZNC}}$ , a net negative charge occurs on the hydroxylated mineral surfaces as reactive  $\text{MOH}$  sites ionise by losing  $\text{H}^+$  to the soil solution ('deprotonation'). That is:

**ALKALINE SOLUTIONS:** when  $\text{pH} > \text{pH}_{\text{PZNC}}$ , then  $\text{MOH} \rightleftharpoons \text{MO}^- + \text{H}^+$  (deprotonation).

Conversely, in acid solutions with solution pH less than  $\text{pH}_{\text{PZNC}}$ , the  $\text{MOH}$  sites ionise to create a positive charge by adsorbing  $\text{H}^+$  from solution ('protonation'). That is:

**ACIDIC SOLUTIONS:** when  $\text{pH} < \text{pH}_{\text{PZNC}}$ , then  $\text{MOH} + \text{H}^+ \rightleftharpoons \text{MOH}_2^+$  (protonation).

The negative charge on the surfaces of variable charge minerals in alkaline solutions can promote the development of a very high cation exchange capacity. As the solution pH decreases, however, the negative surface charge and the CEC diminish, and positive surface charges eventually dominate. In acidic solutions, positive charges predominate on hydroxylated surfaces and the CEC diminishes and vanishes as the anion exchange capacity of the soil (AEC) increases.

In acid solutions, positively charged surfaces on variable charge minerals have a tendency to bond phosphate anions so strongly as to render them immobile. The MOH functional groups of oxides and oxyhydroxides of iron, aluminium, and the hydrated surfaces of the amorphous materials (e.g. volcanic glass) are capable of adsorbing large numbers of phosphate anions. Where M is either Fe or Al, the hydroxyl group is displaced by phosphate anions which bond extremely strongly to the metal cation (McBride 1994).

Crushing the primary mineralogical components of the Fishers Creek Basalt generates large amounts of variable charge on the surfaces of the fine mineral particles. Hydrated volcanic glass, which constitutes some 37% of the basalt (Table 2.2), presents an extremely large area of variable charge surface because the surface is mostly internal. In acidic conditions, it is anticipated that finely crushed samples of the basalt would have a reduced CEC and a strong potential to fix phosphorus from soil solution. Nevertheless, the freshly fractured surfaces of the crushed minerals would provide an initial rapid supply of basic, plant nutrient cations to soil solution when charge-balancing surface cations are exchanged for  $H^+$  ions from solution.

## 2.2.2 Permanent charge surfaces

Illitic and smectitic clays have formed by alteration of the hydrated volcanic glass in the basalt towards the base of the Fishers Creek Quarry (McSkimming 1998). These clay minerals with a sheet silicate structure consist of a single sheet of octahedrally coordinated cations sandwiched between two sheets of silicon-oxygen atoms arranged in linked tetrahedra. Consequently, they are termed '2:1 layer silicate minerals'.

During crystallisation, the 2:1 clays develop permanent negative charges on their surfaces as a consequence of substitutions in the octahedrally or tetrahedrally coordinated layers of one cation for another of similar size but different charge, termed 'isomorphous substitutions'. The permanent charge in illitic clays results largely from the substitution of  $Fe^{3+}$  or  $Al^{3+}$  for  $Si^{4+}$  in the tetrahedral layer. Smectitic clays develop permanent charge by the substitution of divalent cations (e.g.  $Mg^{2+}$  and  $Fe^{2+}$ ) for trivalent cations in the octahedral sheet (e.g.  $Al^{3+}$  and  $Fe^{3+}$ ; Nagy 1995). The ionic substitutions create permanent negative structural changes due to incompletely bonded oxygen atoms, and these charges are balanced by cations that are loosely held between or outside the layers. The interlayer cations are usually hydrated and easily exchanged by other cations in solution.

Permanent charge 2:1 layer silicates typically have high CEC because the layered structure provides a large area of internal surface of permanent negative charge (McBride 1994).

## 2.2.3 Basaltic particle size and cation exchange capacity: results

This section aims to identify the relationship between the particle size of crushed basalt fragments and the amounts of exchangeable basic cations held on the negatively charged sites on the particle surfaces. The sum of the basic exchangeable cations ( $Ca^{2+} + Mg^{2+} + K^+ + Na^+$ ) provides a value for the Effective Cation Exchange Capacity of the soil (ECEC), which has been found to correlate with total CEC calculated by the adsorption of  $Ca^{2+}$  and  $Al^{3+}$  on negatively charged surfaces from a  $CaCl_2$  solution (Gillman and Sumpter 1986a).

Determining the coarsest particle size at which the ECEC of the crushed basalt is maximised will assist in determining the economic cut-off for the energy-intensive and costly grinding process involved in the manufacture of Minplus<sup>TM</sup>.

Samples of the basaltic feedstock from the quarry were sieved through a set of 10 sieves (4.0 mm, 1.4 mm, 1.0 mm, 500  $\mu$ m, 355  $\mu$ m, 250  $\mu$ m, 125  $\mu$ m, 90  $\mu$ m, 64  $\mu$ m) and the modal equivalent spherical diameter of subsamples of each size fraction was determined by a Malvern Mastersizer automatic particle size analyser located in the School of Earth Sciences, James Cook University. On the basis that the particles are considered to be spheres of constant density, the frequency of particle diameters within each size fraction enabled the instrument to provide estimates of the surface area of each size fraction according to the following relationship (McSkimming 1998):

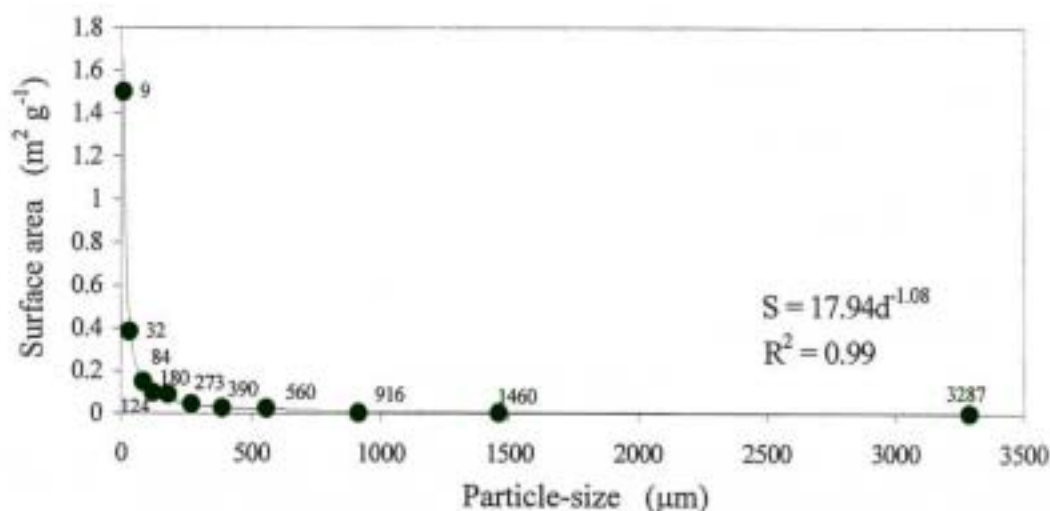
$$S = kd^{-1}$$

where:  $S$  = the particle surface area ( $m^2 / g$ )  
 $d$  = the diameter of the particle ( $m$ )  
 $k$  = a constant relating to the shape and density of the particles,  
and the slope of the relationship between  $\log S$  and  $\log d$  is  $-1$ .

The power formula for the trend of modal particle sizes plotted against estimated surface areas of particles (Fig. 2.1) is in keeping with the idealised relationship described by the preceding equation.

Another set of subsamples of each size fraction of the Fishers Creek Basalt feedstock was washed (aqueous ethanol / aqueous glycerol) to remove soluble salts from the particle surfaces. The exchangeable basic cations were extracted from the variable charge surfaces of the crushed minerals by a 0.1 M  $BaCl_2 / NH_4Cl$  solution using the method of Gillman and Sumpter (1986a). Cation analysis of the centrifuged supernatant liquids were performed on a GBC 932AA atomic absorption spectrometer.

Because the basaltic particles have predominantly variable charge surfaces, the polarity and potential of the surface charge, hence the CEC, was determined by the pH of the extracting solution, which was initially adjusted to neutral. Each exchangeable cation analysis was carried out on 5 replicated samples per determination.



**Fig 2.1 Particle size ( $d$ ) plotted against estimated particle surface area ( $S$ ) for sieved size fractions of the Fishers Creek Basalt; data from Malvern Mastersizer Analyser, James Cook University. Source: McSkimming (1998).**

Results of the CEC analyses are shown in Figs 2.2a – 2.2d in which the data are presented for each particle size class in both  $cmol/kg$  of crushed basalt and  $g / g$  of crushed basalt.

For each of the basic cations analysed, the amount of the exchangeable cation increases as the particle size decreases until a maximum is reached; at this point the finer particle sizes do not appear to exchange more cations from their surfaces. Calcium attained the highest concentrations in the extracting solution ( $\sim 3300 g / g$  of crushed basalt in the 32  $m$  size fraction), potassium was the next most abundant cation ( $\sim 2500 g / g$  also in the 32  $m$  size fraction), while the 9  $m$  size fraction produced just over 500  $g / g$  of exchangeable magnesium.

The average of the sum of the 4 basic cations (in  $cmol/kg$  of crushed basalt) for each of the 5 replicates of each particle size fraction provided a sound basis for determining the effective cation exchange capacity (ECEC) of the fraction. The trend shown in Fig. 2.3 is analogous to that shown for the individual cations. That is, the ECEC increases to a maximum as the particle size of the crushed basalt fraction decreases to 32  $m$ , which is significantly higher ( $p < 0.01$ ) than the ECEC of the 9  $m$  size fraction. Again, such a relationship was not anticipated.

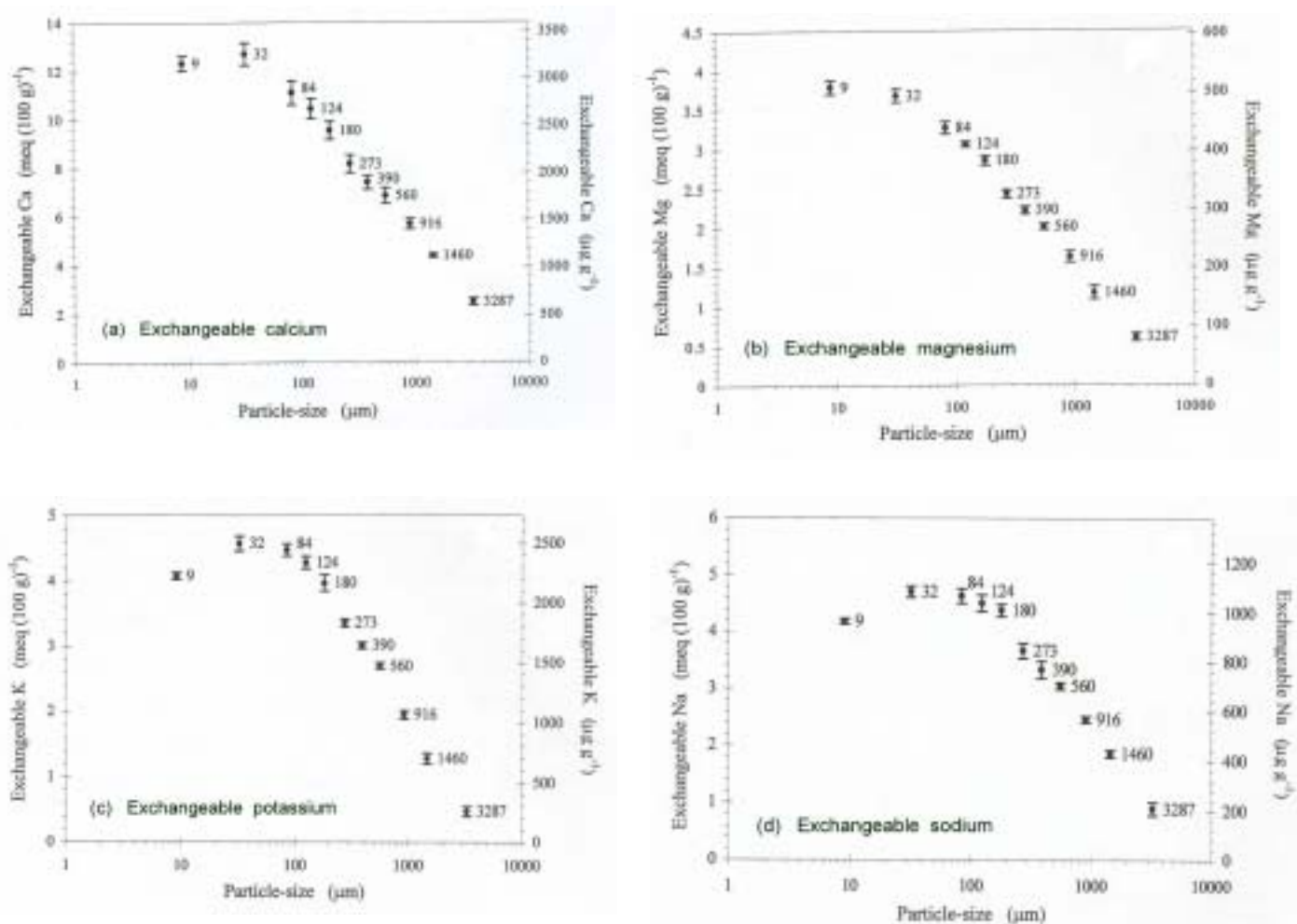


Figure 2.2 Exchangeable basic cation contents of different size fractions of the Fishers Creek Basalt. (a) Exchangeable calcium, (b) Exchangeable magnesium, (c) Exchangeable potassium, (d) Exchangeable sodium. Source: McSkimming (1998).

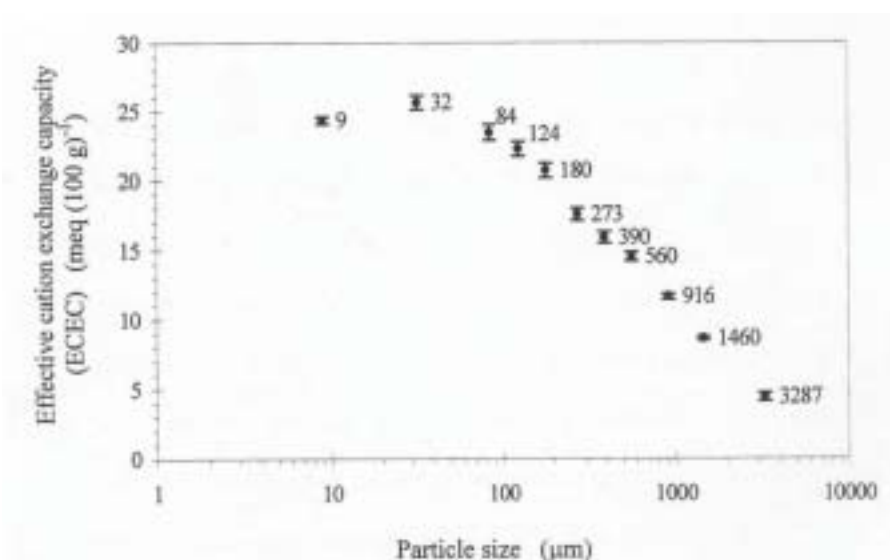


Figure 2.3 Effective cation exchange capacity (ECEC) expressed as cmol/kg of crushed basalt for each particle size class analysed from the Fishers Creek Basalt. Error bars are 2 standard errors; n = 5. Source: McSkimming (1998).



## 2.2.4 Basaltic particle size and cation exchange capacity: discussion

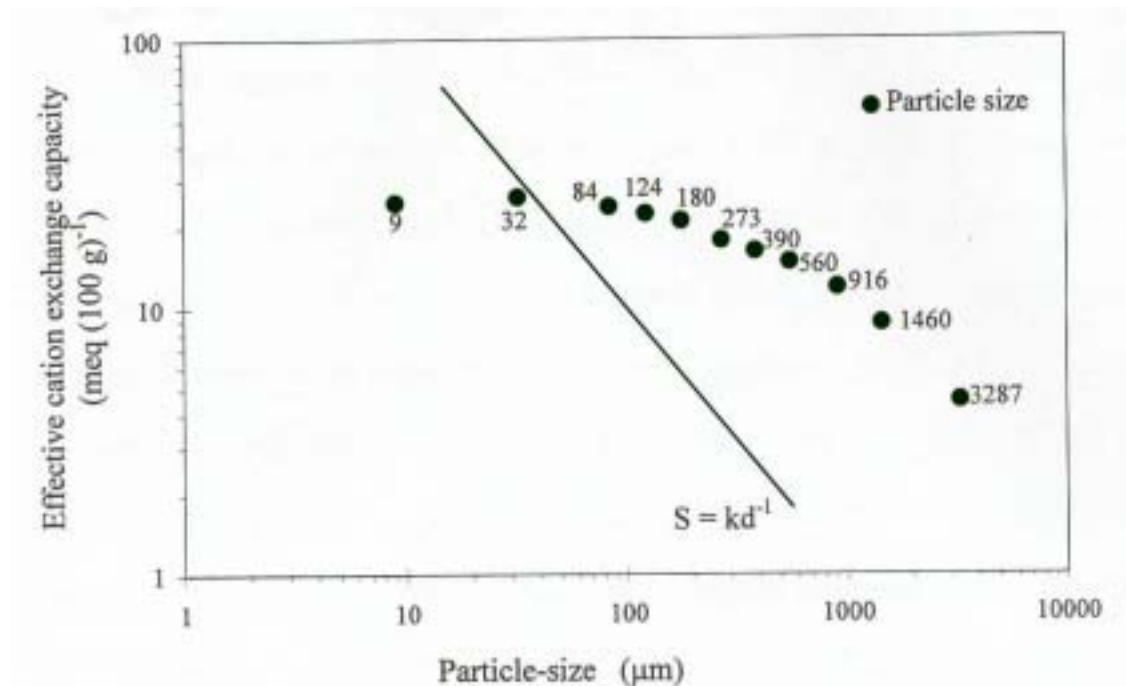
Cation exchange capacity is defined by the formula (Uehara and Gillman 1981):

$$CEC = S$$

where  $S$  = specific surface area per unit mass of material, expressed as  $\text{cm}^2/\text{g}$   
 = surface charge density per unit area, expressed as  $\text{esu}/\text{cm}^2$

The particle size fractions are all composed of the same crushed basaltic material. It was expected that differences in the surface charge density of the particles would be minimal, especially in the coarser size fractions. Hence, the relationship between ECEC and particles of decreasing size was expected to be linear and due entirely to the increase in specific surface area ( $S$ ).

A plot of  $\log [\text{ECEC}]$  against  $\log [\text{particle diameter}]$ , and a plot of  $\log [\text{external surface area created by crushing}]$  against  $\log [\text{particle diameter}]$ , show different slope relationships (Fig 2.4). This indicates that there is no simple relationship between ECEC and the external surface area created by the crushing process. Hence, it may be concluded that the charged surfaces of the basaltic particles relate to processes other than those of simple size reductions brought about by crushing the basalt.



**Figure 2.4** Effective cation exchange capacity (ECEC) for different particle size classes of crushed basalt, and the theoretical relationship between surface area ( $S$ ) and particle size ( $d$ ). Note the logarithmic scales on both axes. Source: McSkimming (1998).

The crushed particles of the hydrated volcanic glass that constitutes such a large amount of the Fishers Creek Basalt has an internal surface due to the microporosity and permeability of the structure of the glass. The internal surfaces of the glass, and the external surfaces of the crushed particles, both carry variable charge. Their relative contributions to the total CEC is determined by the ratio of internal charge surface to external charge surface ( $S_{INT} : S_{EXT}$ ), which is dependent on the sizes of the particles. At very fine particle sizes, the external surface will be larger than the internal surface, and the opposite is true for very coarse particles. At a specific particle size, the external surface area of the particles will be greater than the area of the internal surfaces carried by the hydrated glass.

The issue is also influenced by the difference in the nature of the surface charge density ( ) between internal and external surfaces. Parks (1990) has shown that the surface charge density in the concentric structural voids of

the internal surfaces is likely to be greater than the charge density on the planes defined by the external mineral surfaces.

The potential for an extracting solution to remove cations from the hydrated glass matrix will decrease as the particle size increases because, in the larger particles, the permeability gradient increases towards the centres of the particles (Gregg and Sing 1982). Also, the interconnecting fabric of the hydrated glass matrix would be reduced in the larger particles where there is a greater chance that some of the hydrated glass will be isolated by surrounding crystals and made inaccessible to the extracting solution (Gregg and Sing 1982).

The inflection in the relationship between ECEC and particle size at 32  $\mu\text{m}$  (Fig. 2.3) is possibly due to the behaviour of clay colloid particles ( $< 2 \mu\text{m}$ ) in the finest size-classes. Particles between 0.5  $\mu\text{m}$  and 2  $\mu\text{m}$  in size tend to flocculate as a result of very large negative charges on their external surfaces bonding to similarly large positive charges on adjoining particles causing the particles to adhere (van Olphen 1977; Gregg and Sing 1982). Flocculation causes a reduction in the surface charge potential of colloids because most of the high potential charge sites gain electrical neutrality by flocculation, leaving a surface with only relatively weak positive and negative charge (van Olphen 1977). The particle size fraction with a modal diameter of 9  $\mu\text{m}$  produced a lower ECEC, probably as a result of flocculation of colloids causing a reduction in the charge density ( $\rho$ ) on external surfaces.

The existence of internal surfaces in the hydrated glass matrix of the Fishers Creek Basalt provides flexibility when determining the optimal particle size to which the basalt should be crushed in order to yield the maximum amount of exchangeable basic cations. Based on Fig. 2.3, it is recommended that the basalt be crushed to particles with a diameter less than 200  $\mu\text{m}$ . This will result in a finely crushed soil amendment with a range of particle sizes up to 200  $\mu\text{m}$ , and an ECEC (at pH 7) of 20 – 25 cmol/kg of crushed basalt.

Trying to further reduce the size of the particles by crushing will only serve to waste energy.

## 2.3 Mineral additives

The Fishers Creek Basalt contains appreciable quantities of the major plant nutrients calcium and magnesium, lesser amounts of phosphorus and potassium, and no sulphur or nitrogen (Table 2.1). While nitrogen rarely occurs in rock minerals, other macronutrients that are deficient in basalt are commonly found in other rocks. A potassic granite, gypsum, and rock phosphate have been studied in relation to their potential to supplement Minplus<sup>TM</sup> with potassium, sulphur, and phosphorus respectively (Table 2.3).

**Table 2.3 Comparison of selected chemical properties the potassium-rich Sybella Granite (less than 125  $\mu\text{m}$  size class) with those of the Fishers Creek Basalt (32  $\mu\text{m}$  modal size class). Total values determined by X-ray fluorescence spectrometry at the Advanced Analytical Centre, James Cook University, exchangeable cation values by method of Gillman and Sumpter (1986a). Source: McSkimming (1998).**

Chemical Property		Fishers Creek Basalt	Sybella Granite	Duchess Rock Phosphate	Winton Gypsum
Total nitrogen	%	0.0	0.0	0.0	0.0
Total phosphorus	%	0.3	0.1	10.3	0.1
Total potassium	%	1.3	4.7	0.5	0.8
Total calcium	%	6.5	1.2	24.8	23.7
Total magnesium	%	6.4	0.2	0.4	0.6
Total sulphur	%	0.2	0.0	0.3	23.6
Exchangeable calcium	cmol/kg	12.69 *	1.75 *	n.d.	n.d.
Exchangeable magnesium	cmol/kg	3.68 *	0.35 *	n.d.	n.d.
Exchangeable potassium	cmol/kg	4.57 *	1.27 *	n.d.	n.d.
Exchangeable sodium	cmol/kg	4.71 *	0.35 *	n.d.	n.d.
Effective cation exchange capacity (ECEC; cmol/kg)		25.65 *	3.72 *	n.d.	n.d.

\* Differences between means is significant ( $p < 0.01$ ). 'n.d.' = not determined.

### 2.3.1 Potassium from alkali granite

The chief mineral components of alkali granite are feldspar, biotite mica, and quartz. Feldspar and biotite contain potassium, which in crushed rock is made available to plants in solution by exchange from charged surfaces created during grinding and by dissolution. The framework structure of feldspar crystals ensures that the rate of potassium release from the crystal lattice by dissolution is very slow (Bernere 1978). Biotite, a sheet silicate, is more vulnerable to dissolution than feldspar because Fe in the structure readily oxidises and is removed from the crystal by dissolution.

The Sybella Granite, located some 150 km south of Mt Isa, has a total potassium content of 4.7% (McSkimming 1998) compared with 1.4 % for the Fishers Creek Basalt (Table 2.1). The Sybella Granite is one of the most potassium-rich granitic rocks in north Queensland. It is a coarse grained rock with crystals of 10 – 50 mm. When ground in a ball mill, the rock rapidly breaks down to a bimodal size distribution with quartz grains of grains of about 15 mm and a fine powder of the other rock constituents, which readily passed through a 125  $\mu$ m sieve. The rarity of materials between 125  $\mu$ m and 15 mm in size probably reflects shearing along planes in crystal lattices producing the fine powder.

The granite crushed to less than 125  $\mu$ m revealed a particle size distribution similar to that of the 32  $\mu$ m crushed basalt size fraction. Accordingly, the exchangeable cation contents of these size fractions of the two materials were compared (Table 2.3). The granite clearly provides less potassium by ion exchange than does the basalt; similarly, the effective cation exchange capacity of the Sybella Granite was less than one third of that of the Fishers Creek Basalt (Table 2.3).

The potential of the Sybella Granite as a source of a potassium supplement for Minplus<sup>TM</sup> is extremely limited, despite granitic rocks being used nationally and internationally as the base ingredients in numerous commercial soil amendment products (Campe 1996; Harley 2000). Given that the Sybella Granite is one of the most potassium-rich granites in the region, it is unlikely that other readily available rocks in north Queensland would perform better as a potassium supplement.

### 2.3.2 Phosphorus from rock phosphate

The rock phosphate used in the present study was supplied as a finely ground powder by the Burdekin Lime Company, Ayr, from a dried tailings dam filled during mining of rock phosphate at Duchess, near Mt Isa in northwestern Queensland, some 15 years ago. The particle sizes of the powder ranged up to 200  $\mu$ m and its chemical properties are shown in Table 2.3.

By dissolution in 0.005 M sulphuric acid at pH 2.2, each gram of rock phosphate yielded 32,174  $\mu$ g (standard error = 172.2  $\mu$ g) of phosphorus to solution, compared with a maximum of 1,193  $\mu$ g (standard error = 13.2  $\mu$ g) per gram of crushed basalt with a modal particle size of 124  $\mu$ m (McSkimming 1998). While some of the phosphorus dissolved from the crushed basalt may have become unavailable by sorption to variable charge sites, the basalt cannot yield more than 3,100  $\mu$ g of phosphorus per gram of basalt, which is the total phosphorus content of the basalt (Table 2.3).

Researchers investigating the fertilising potential of rock phosphates from around the world (Bolland and Gilkes 1989, 1997; Bolan *et al.* 1990; Barbere *et al.* 1998) have found that the Duchess Rock Phosphate is unreactive and of low agronomic value compared with other rock phosphates. Nevertheless, Bolland *et al.* (1997) gained some benefit from applications of Duchess Rock Phosphate to a tropical pasture on a highly leached, acidic soil near Tully, north Queensland.

When added to soils with other amendments that increase the soil pH and / or the exchangeable calcium content of the soil, the rates of dissolution of rock phosphates are known to be reduced. Chien and Menon (1995) found that liming was detrimental to rock phosphate dissolution. He *et al.* (1996) amended acidic soils with rock phosphate supplemented with lime and gypsum, both of which reduced the amount of rock phosphate dissolved. In combinations of lime + gypsum + rock phosphate, dissolution of the rock phosphate was drastically reduced compared with its solubility in the presence of just one of the amendments (He *et al.* 1996).

The high concentration of phosphorus in the Duchess Rock Phosphate, and the increased solubility of apatite [ $\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$ ] at low pH (Hammond *et al.* 1986), make this rock a strong contender for use as a phosphorus

supplement in basaltic soil amendments. The apatite will dissolve fastest from the finest particles in the more acidic soil solutions. The liberated phosphorus may not be available for plant uptake, however, as a consequence of the phosphate fixing sites on variable charge surfaces present on crystalline iron and aluminium oxides and amorphous oxyhydroxides. These surfaces occur on minerals common to both the crushed basaltic soil amendment and acidic tropical soils.

It is predicted that, unless the soil solution is amended by raising its pH and risking a reduction in rock phosphate solubility, much of the phosphorus contained within the basaltic soil amendment may be unavailable to plants.

### **2.3.3 Sulphur from gypsum**

The gypsum [ $\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$ ] used was also supplied as a fine powder by the Burdekin Lime Company, Ayr, from a quarry in lacustrine sediments near Winton, north-western Queensland. The soluble nature of the gypsum ensures that its high contents of calcium and sulphur (Table 2.3) are available to soil solutions.

In soils where dissolved constituents are not rapidly lost by leaching, minimal applications of 10 – 100 kg / ha of gypsum are adequate to supply plant sulphur requirements (Roberts 1987; Troeh and Thompson 1993).

The longevity of gypsum in the soil is uncertain. Sumner *et al.* (1986) found that, after tilling 10 t/ha of granular gypsum into an acidic soil in Georgia, USA, the sulphur content of alfalfa plant tissues increased continuously over the 4 year life of the experiment. The increase in alfalfa yield occurred concurrently with a 15% decrease in toxic  $\text{Al}^{3+}$  in soil solution as a result of the formation of non-toxic  $\text{AlSO}_4$ . Couto *et al.* (1979) and Ritchey *et al.* (1980) recorded an increase in cation exchange capacity when gypsum was applied to acidic soils containing iron and aluminium oxides and oxyhydroxides. They suggested that the sulphate anion is specifically sorbed by such minerals and results in increased negative charge on the mineral surface which, in turn, increases the CEC of the soil.

Gypsum appears to have potential as a sulphur supplement in crushed basaltic soil amendments and further examination is recommended. Of particular relevance is research into altering the particle size of the gypsum grains as a way to control their solubility (McSkimming 1998).

### 3. Properties of Minplus<sup>TM</sup>-treated soils

An attempt is made in this chapter to summarise the results of research has been carried out into a range of soil properties that are important to plant growth in the humid tropics, principally:|

- soil pH,
- cation exchange properties,
- electrochemical (charge) characteristics,
- extractable, or 'plant available' phosphorus and silicon,
- phosphorus fixation capacity of the soil.

#### 3.1 The studied soils

To evaluate the effect of the crushed basaltic soil conditioner, Minplus<sup>TM</sup>, on the chemical properties of highly weathered soils, a suite of surface soil samples was collected from the 0 – 10 cm layer from a range of soils from the humid tropical coast of Queensland. The soils were sampled from sites between the North Johnstone and Tully Rivers, between Innisfail and Tully (Fig. 3.1). Murtha (1986) recognised 43 soil series within this area, and Gillman and Abel (1987) and Murtha and Smith (1994) have provided detailed descriptions of their characteristics.

From these soil series, seven soils were selected for the present project the Tyson, Galmara, Pin Gin, Mundoo, Innisfail, Tully, and Kurrimine Series (Table 3.1). The soils are important for the cultivation of extensive fruit, vegetable, sugarcane crops, and forestry plots in the area. The soils have formed on a variety of geological substrates: granitic, metamorphic, and basaltic rocks and in unconsolidated alluvium and beach sands derived from mixtures of the rock types (Fig. 3.1). The variety of soils selected allows an evaluation of the amendment's effects on soil types, which have different mineralogical, chemical, physical, and biological characteristics as a result of their different parent materials.

##### 3.1.1 Soil samples and their preparation

Soil sample sites were chosen as closely as possible to the original sample sites of Murtha (1986) and, in all but the extensively cleared Innisfail and Mundoo Soils, at locations with undisturbed rainforest vegetation.

Approximately 70 kg of each of the 7 soils was collected from the 0 - 10 cm depth in each soil profile. The bulk samples were air-dried and sieved to 2 mm. The bulk sample was then divided into 45 subsamples each weighing approximately 1.5 kg. The field capacity was determined by the method of Black *et al.* (1965). Two size grades of Minplus<sup>TM</sup> ('Standard' Minplus<sup>TM</sup> < 250  $\mu$ m nominal particle size; and 'Superfine' Minplus<sup>TM</sup> < 40  $\mu$ m nominal particle size) were thoroughly mixed into 5 separate replicates of each of the surface soil samples at application rates equivalent to 0, 1, 5, 25, and 50 t/ha.

The water content of each soil sample was raised to field capacity with the incorporation of 0.004% copper sulphate solution to eliminate fungus growth. Soils were then incubated for 3 months, in plastic bags in the dark, to allow reactions to occur between the soil and the amendment. After the incubation period, samples were air-dried to halt the soil processes in preparation for chemical analysis.

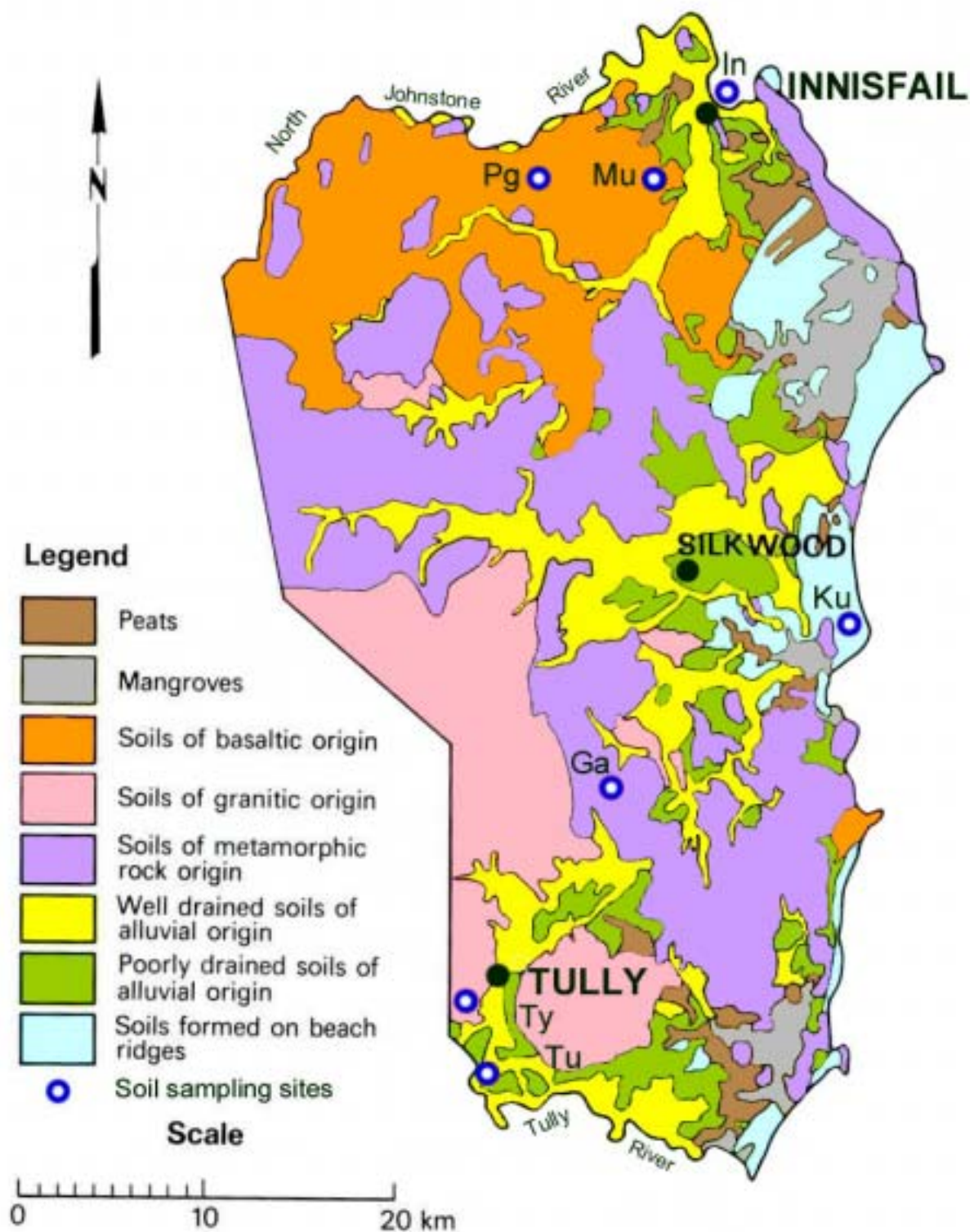


Figure 3.1 Distribution of soils and their parent materials in the Innisfail – Tully area, north Queensland. Source: Murtha (1986).

Sampling sites for 7 studied soil series are shown as follows:

Galmara (Ga), Innisfail (In), Kurrimine (Ku), Mundoo (Mu), Pin Gin (Pg), Tully (Tu), Tyson (Ty).

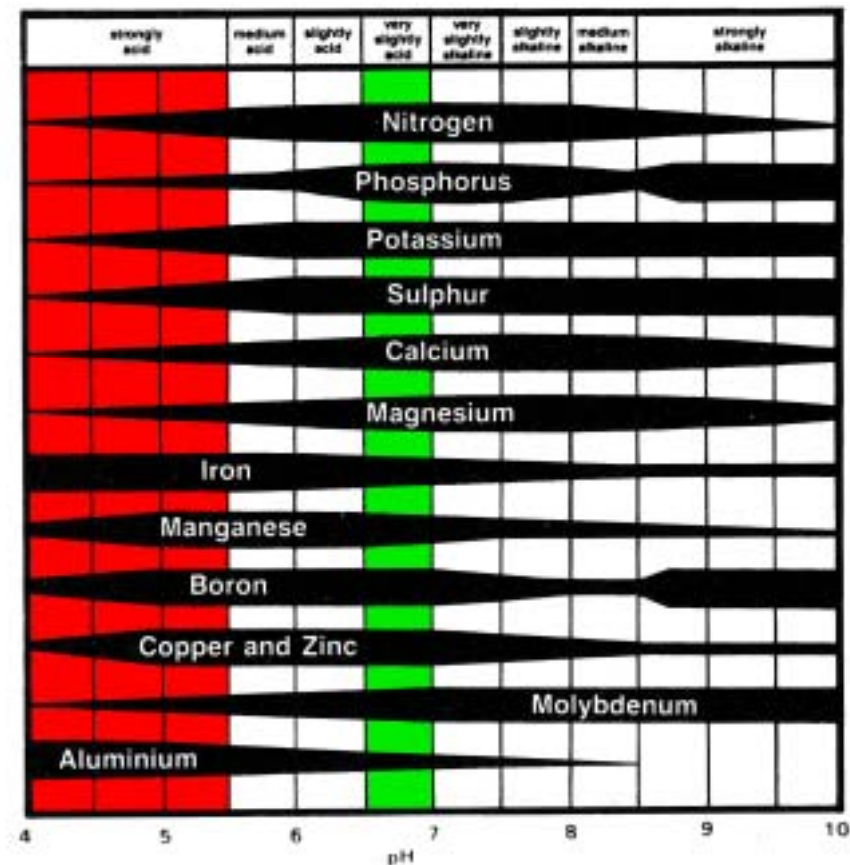
**Table 3.1 Main characteristics of the seven studied soils from the humid tropical Tully – Innisfail area, north Queensland.**  
**Sources: Murtha (1986); Gillman and Abel (1987).**

	Soil Series and Type Profile Number	Soil Parent Material	Soil Landscape	Soil Profile Characteristics	Characteristics of 0-10 cm topsoil layer							
					Sand	Silt	Clay	pH	CEC	Organic matter	Total P	Plant available P
					%	%	%		cmol/kg	%	%	ppm
27	<b>Tyson</b> T 241	Granite or granitic alluvium	Granitic bedrock or upper slopes of steep alluvial fans	Uniform or gradational texture profile; red, massive, B horizon	67	2	31	5.4	3.2	3.57	0.020	13
	<b>Tully</b> T 257	Granitic alluvium	Stream levees, flood plains, and terraces	Uniform or gradational texture profile; yellow, structured B horizon	31	29	40	4.8	6.8	3.91	0.058	27
	<b>Pin Gin</b> T64	Basalt	Strongly undulating, low hills	Very deep, uniform or gradational texture profile; dark red, strongly structured B horizon	13	19	68	5.3	6.6	5.78	0.162	11
	<b>Mundoo</b> T 280	Basaltic alluvium	Lower slopes of broad, low angle alluvial fans	Gradational texture profile; dark red, strongly structured B horizon; minor basaltic gravel	49	10	41	4.9	2.4	2.38	0.240	68
	<b>Innisfail</b> T 281	Mixed basaltic and stream alluvium	Stream levees and floodplains	Uniform or gradational texture profile; brown or reddish brown, structured clay B horizon	30	27	43	4.9	6.3	2.04	0.200	38
	<b>Galmara</b> T 258	Barron River Metamorphic rocks	Low, moderately undulating hills	Uniform or gradational texture profile; red, structured B horizon	68	9	23	4.7	10.0	3.74	0.019	68
	<b>Kurrimine</b> T 212	Sandy quartzitic sediments	Old, stranded beach ridges	Well developed sandy podzol profile with dark sandy A1 horizon; prominent bleached A2 horizon; dark coloured, cemented B horizons	97	1	2	4.5	3.7	n.a.	0.004	n.a.

## 3.2 Soil acidity

### 3.2.1 Problems of acidic soils

Like many of the highly weathered soils of the humid tropics of north Queensland, the pH of samples from the 7 untreated soils studied were found to vary from 4.5 to 5.4 (Table 3.1). Such strongly acidic soils present a number of constraints to plant growth as a consequence of the lack of availability of some plant nutrients, or of the oversupply of other elements that are antagonistic to plant growth (Fig. 3.2).



**Figure 3.2** The effect of soil pH on the availability of plant nutrients. The widths of the bars indicate the relative availability of plant nutrients. Source: Ward (1998).

The optimal availability of most plant nutrients lies in the range of pH 6.5 – 7.0. Few of the essential plant elements are available in any abundance in strongly acidic soils. Manganese becomes increasingly available as the soil pH falls and reaches toxic levels in the soil when the pH is less than 5.5. Similarly, aluminium becomes toxic in most soils with pH less than 5.0. A commonly used method to overcome manganese and aluminium toxicities in acidic soils is to apply lime or dolomite to raise the soil pH.

### 3.2.2 Raising the pH of acidic soils

Soil acidity is a major constraint to plant growth throughout the world, and is one of the most widespread soil problems of the humid tropics. Land managers aim to raise the pH of acidic soils to the range preferred by the specific crop in order to provide a balanced supply of plant nutrients, to promote growth, and to enhance yields. The plants respond better in less acidic soils to fertiliser additions through the increased availability of essential plant nutrients such as molybdenum (Fig. 3.2). Reduced soil acidity enhances legume growth by providing a more suitable environment for microbial activity in the soil, which also provides longer term benefits to the soil through greater nitrogen fixation in root nodules.

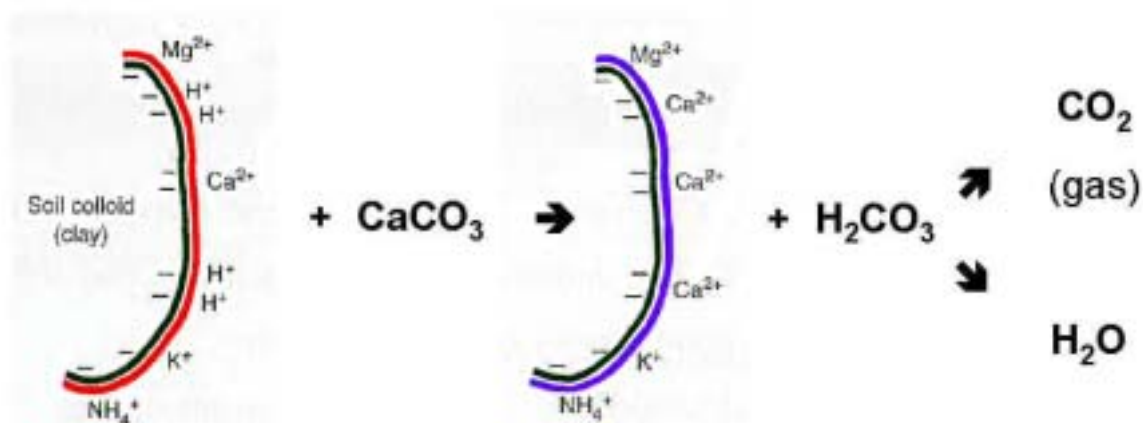


Soil acidity may be reduced (i.e. soil pH increased) through the addition of lime [crushed limestone,  $\text{CaCO}_3$ ], dolomite [ $\text{CaMg}(\text{CO}_3)_2$ ], quicklime [ $\text{CaO}$ ], slaked lime [ $\text{Ca}(\text{OH})_2$ ], or marl [crushed freshwater limestone,  $\text{CaCO}_3$ ] to the soil in amounts that are determined by the ‘buffering capacity’ of the soil, which is a measure of the ability of the soil to cushion itself from changes in soil pH caused by the addition of alkalis or acids to the soil. Soils with high cation exchange capacities have the greatest abilities to withstand changes in pH. Hence, the buffering effects are greatest in organic-rich clays and least in sands. The amount of acid neutralising agent required to effect a change in soil pH depends on a number of variables: the amount of change in soil pH that is required, the buffering capacity of the soil, the chemical composition (‘neutralising value’) of the agent to be used, the purity of the agent, and the fineness of the agent.

### 3.2.3 The down-side of liming

The spreading of lime at application rates of 1 – 10 t/ha to neutralise acidic soil conditions is a common, but inappropriate practice in many farming and industrial situations. Beneficial effects of lime or dolomite applications are generally short-lived under the heavy soil leaching processes that prevail in humid tropical conditions. The soil may require large quantities of lime to raise the soil pH to an appropriate level throughout the root zone.

Lime neutralises the active soil acidity by reacting with protons [ $\text{H}^+$  ions] on colloid surfaces which cause the acidity. Carbonic acid [ $\text{H}_2\text{CO}_3$ ] is formed which then breaks down to water and carbon dioxide gas (Fig. 3.3). For every tonne of lime that is applied to the soil, 400 kg of carbon dioxide will eventually be released into the atmosphere as an inevitable consequence of neutralising soil acidity.



**Figure 3.3 Neutralising active soil acidity with lime.** Protons ( $\text{H}^+$  ions), displaced from the surface of the acidic colloid by calcium cations from the lime, react with carbonate anions from the lime to produce carbonic acid. The carbonic acid breaks down in the soil to liberate water and carbon dioxide, a greenhouse gas. For every tonne of lime applied to the soil, 400 kg of carbon dioxide are released into the atmosphere.

Lime use in Australia in 1995-96 was 1,622,000 tonnes (Merry and Janik 1999), which has the potential to release at least 648,800 tonnes of carbon dioxide gas annually. Production of 1 Megawatt of electricity by a coal-fired power station will liberate 1 tonne of carbon dioxide (Mr Derrick Cameron, Ergon Energy, pers. comm.), and a “normal household” will use 8 MW hours / year of electricity.

Hence, the 648,800 tonnes of carbon dioxide liberated from Australia’s use of agricultural lime in one year is equivalent to the carbon dioxide emissions from a coal-fired power station with the capability of producing enough electricity to support a community of 81,000 households. Given an average household of 3.5 people, the annual use of lime in Australia releases a similar amount of carbon dioxide into the atmosphere as would coal-fired electricity generation to support a population of 283,000 people for a year. This number is close to the total population of north Queensland, including the cities of Townsville and Cairns!

### 3.2.4 Using Minplus™ to neutralise soil acidity

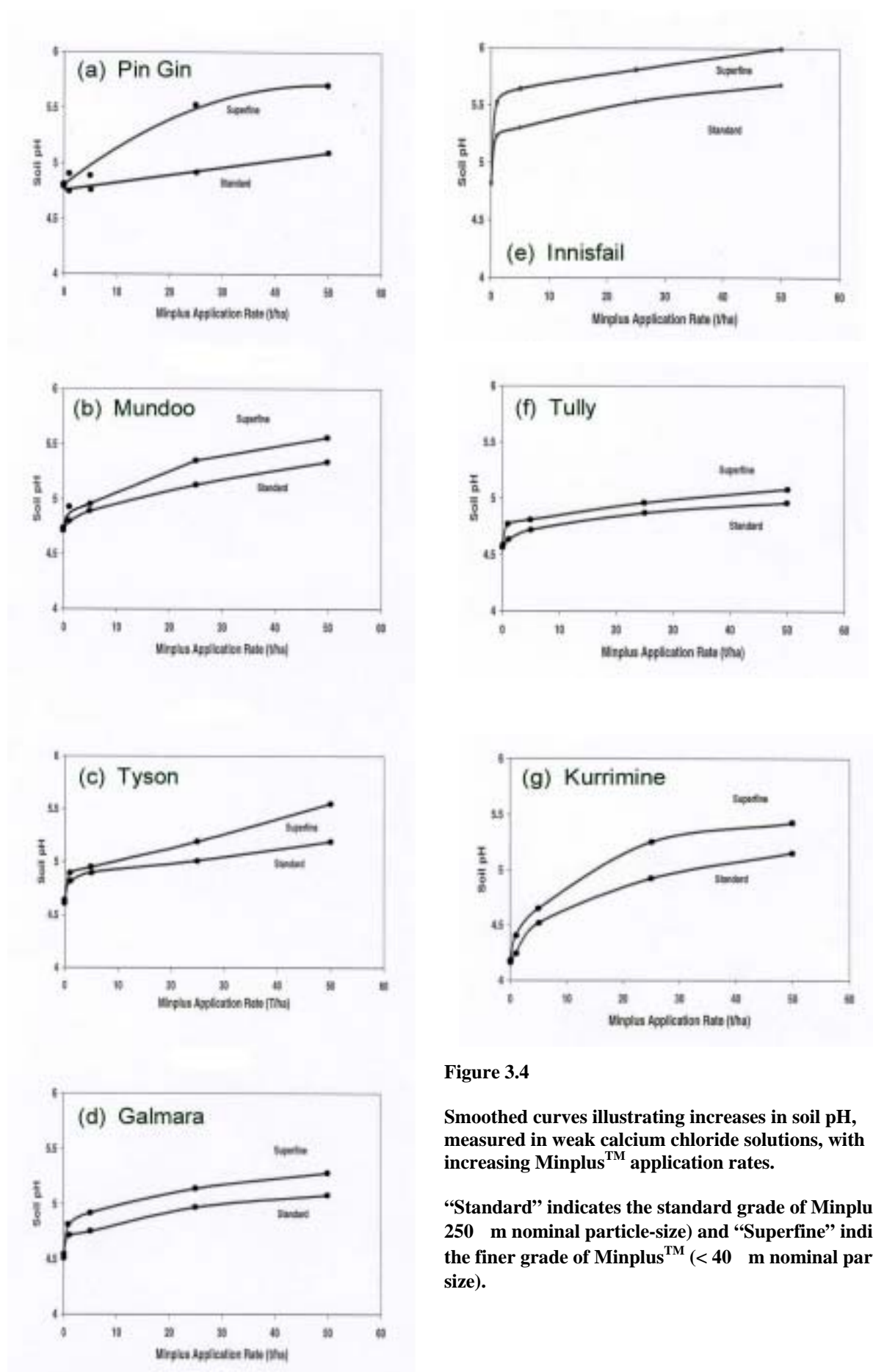
Research conducted in Queensland, Mauritius, Hawaii, Florida, and Brazil (Section 1.3, above) has shown that silicate-based rock dusts may be very effective “liming materials”, or soil acidity neutralising agents. Crushed basalt has an abrasion pH of about pH 8. Thus any liming mechanism will operate by neutralising acidity present in the soil solution, i.e. the *active acidity*, which will be registered as an increase in soil pH, and also by neutralising the acidic cations (H+Al) present on the exchange complex, i.e. the *reserve acidity*. The latter would be demonstrated as an increase in base saturation (i.e. a reduction in base unsaturation).

Designation of some single pH value as an optimum pH for the 7 studied soils is not appropriate. Clay mineralogical composition largely determines the pH at which base saturation is optimal, and there are differences in clay content and composition among the soils (Table 3.1). Also, the choice of optimum soil pH will depend on the plants to be grown, since plant species vary greatly in their tolerance to soil acidity.

Soil pH was determined on 0.002 M calcium chloride solutions (Rayment and Higginson 1992). Clear differences in soil pH are evident in Fig. 3.4 and, in all cases, increasing rates of Minplus™ applications from 1 t/ha up to 50 t/ha have produced significant increases of between 0.3 and 1.0 pH units in all of the 7 soils studied. The smoothed curves of Fig. 3.4 show steady increases across the entire Minplus™ application range in some soils whilst, in other soils, the soil conditioner produced a sharp pH increase at an initial application rate of 1 t/ha, and a more gradual increase in soil pH with further additions.

Determination of soil pH is a measure of the active acidity in soil, i.e. of the acidity present in the soil water. Of greater importance in many cases is the reserve acidity, the amount of H + Al cations occupying cation exchange sites. This reserve acidity controls the active acidity, and acts to replenish it when liming materials are added to soil. A liming program, therefore, must ensure that sufficient amendment is applied to the acidic soil to neutralise both active and reserve acidity.

The summary of acidic cation (H + Al) contents shown in Table 3.2 shows the efficiency of the ameliorating effect of Minplus™ applications on reserve acidity in the 7 studied soils. Soils formed on basaltic materials generally do not have high levels of reserve acidity (Gillman and Sumpter 1986b), explaining the low levels of H + Al cations in the Pin Gin, Mundoo, and Innisfail Soils, even where no Minplus™ has been added.



**Figure 3.4**

Smoothed curves illustrating increases in soil pH, measured in weak calcium chloride solutions, with increasing Minplus™ application rates.

“Standard” indicates the standard grade of Minplus™ (< 250  $\mu$ m nominal particle-size) and “Superfine” indicates the finer grade of Minplus™ (< 40  $\mu$ m nominal particle-size).

The soil conditioner, therefore, has had only a small effect on the lowering of these values. The other four soils, on the other hand, have appreciable amounts of reserve acidity, and this has been considerably reduced following Minplus™ applications, often at quite low application rates (Table 3.2). With the possible exception of the Tully Soil, the H + Al cation contents have been reduced to amounts considered harmless, by addition of up to 50 t/ha Minplus™. As would be expected, the Superfine grade of Minplus™ (< 40 µm nominal particle size) has had a slightly greater effect than the coarser (< 250 µm) Standard grade Minplus™.

Hence, Minplus™ can provide the benefits of liming without the emission of carbon dioxide or other greenhouse gases. In addition, Minplus™ addresses the additional problem of phosphorus fixation in acidic, iron-rich, highly weathered soils, which is discussed below (Section 3.4).

**Table 3.2 The effect of Minplus™, applied at different rates of Standard grade (< 250 µm) and Superfine grade (< 40 µm), on the amount of exchangeable acidity (H<sup>+</sup> + Al<sup>3+</sup> cations; cmol/kg) in the 7 studied soils from the humid tropical Innisfail - Tully area, north Queensland.**

Soil	Minplus™ grade *	Minplus™ application rate (t/ha)				
		0	1	5	25	50
Pin Gin	Standard	0.33	0.36	0.37	0.26	0.16
	Superfine	0.33	0.35	0.34	0.21	0.23
Mundoo	Standard	0.25	0.23	0.21	0.10	0.10
	Superfine	0.25	0.21	0.18	0.11	0.12
Tyson	Standard	1.04	0.72	0.54	0.35	0.18
	Superfine	1.04	0.58	0.43	0.21	0.14
Galmara	Standard	1.33	1.05	0.96	0.54	0.36
	Superfine	1.33	0.96	0.72	0.44	0.35
Innisfail	Standard	0.35	0.27	0.22	0.21	0.21
	Superfine	0.35	0.19	0.16	0.15	0.15
Tully	Standard	1.99	1.84	1.59	1.03	0.62
	Superfine	1.99	1.82	1.46	0.69	0.39
Kurrimine	Standard	1.10	0.90	0.50	0.16	0.08
	Superfine	1.10	0.80	0.44	0.09	0.08

\* Nominal particle sizes of the Standard grade Minplus™ is < 250 µm, and of the Superfine grade Minplus™ is < 40 µm.

### 3.3 Cation chemistry of Minplus™-treated soils

#### 3.3.1 Cation exchange capacity of highly weathered soils

Soils of the high rainfall tropics, including the coastal region of tropical Queensland (Fig. 3.1), are formed under intense leaching conditions and, consequently, are highly weathered. In less humid environments, soils can also be highly weathered if they have been subjected to less intense weathering, but over long periods of time. Advanced weathering, for whatever reason, leads to soils containing significant amounts of the clay mineral kaolinite and minerals consisting of oxides and oxyhydroxides of iron and aluminium in their colloidal fraction.

The CEC of these types of soil is not a fixed quantity, and is in fact dependent upon soil pH. As the soil becomes more acid, the surface negative charge (the CEC) decreases, and the capacity to retain plant nutrient cations against leaching is diminished. Soils with CEC that is dependent upon pH are termed **Variable Charge Soils** (Section 2.2.1, above). Compared to their less weathered counterparts in the world temperate regions, variable charge soils have low CEC even at neutral pH values, and acidification further exacerbates this problem of low cation retention ability.

Soil organic matter is negatively charged, and constitutes an important source of CEC in variable charge soils. Under undisturbed conditions, such as those found under natural rainforests, soil organic matter levels are

relatively high. A large proportion of the organic matter is usually lost when the trees are cleared, the soil cover removed, and cultivation commenced. In fact, forest clearing and cultivation often result in both loss of organic matter and increased soil acidification – conditions which result in soils with very low CEC and low base saturation. In a humid tropical environment it is almost impossible to increase soil organic matter levels if the soil is regularly cultivated using conventional techniques.

### 3.3.2 Crushed basalt rock as a potential soil conditioner

Basalt rock is a basic material, rich in calcium, magnesium, and to a lesser degree potassium silicates. Potentially, it has the capacity to restore the major nutrient cations (Ca, Mg, K) often found to be deficient in highly weathered soils. When finely crushed, it exhibits a high abrasion pH, and therefore has the ability to neutralise soil acidity, and reduce the toxic effects of exchangeable aluminium in strongly acid soils, i.e. it has 'liming' properties. In addition, theory predicts that it should be able to increase the CEC of soils by two principal mechanisms:

- increasing the soil pH, hence increasing the negative charge on soil variable charge components (as explained above);
- increasing the CEC of certain soils when silicate anions are adsorbed onto positively charged particle surfaces, thereby increasing surface particle charge.

Being a rock material, basalt is relatively insoluble, but solubility can be greatly enhanced by crushing the rock to a fine powder, increasing its surface area by several orders of magnitude. When added to moist soil, its ameliorative action will be highly dependent upon the following:

- properties of the soil itself,
- rate of application of the amendment,
- degree of fineness to which it has been crushed,
- time of contact between the ameliorant and soil,
- environmental (particularly rainfall) conditions subsequent to amelioration.

These factors need to be thoroughly understood in order to be able to interpret the results from any field trials undertaken with Minplus™ as a soil conditioner.

### 3.3.3 Experimental approach

The effects the application of the Minplus™ soil conditioner to the soils was elucidated by a series of routine soil tests. The tests quantified increases in nutrient cation content, decreases in exchangeable acidic cations, and increases in the capacity of the soil to retain nutrient cations, using the following methods:

- *Cation and anion exchange capacity*

Soil cation and anion exchange capacities (CEC and AEC, respectively) were determined routinely by the Gillman and Sumpter (1986b) method where the amount of  $Mg^{2+}$  that can be absorbed at the 'field' pH of the soil and the ionic strength of the soil solution are measured.

- *Exchangeable basic cations (Ca, Mg, K, Na)*

After determining the CEC and AEC of the soil using the Gillman and Sumpter (1986b) method, the contents of basic cations in the supernatant  $MgSO_4$  were determined by atomic absorption spectrometry.

- *Exchangeable acidic cations (Al + H)*

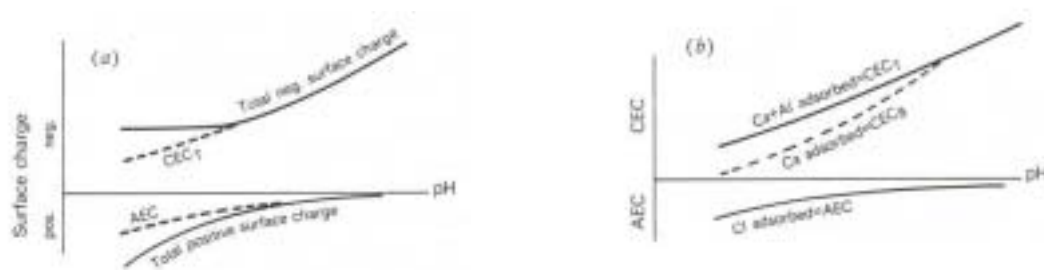
The method used in this analysis was a variation on the exchangeable acidity method 15G1 of Rayment and Higginson (1992). This method equilibrated the soil with 1M KCl for 1 hour at a soil : solution ratio of 1 : 10. The filtered extract was then titrated to pH 8.0 against an NaOH of known molarity. Acidic cation contents were then calculated from the amount of NaOH required for the titration.

- *Charge Fingerprint*

It is equally important that the mechanisms by which any changes in the soil are achieved by applications of Minplus™ are understood, to allow possible manipulation in an effort to obtain maximum advantage from the amendment or its improved formulations. Therefore, a non-routine analytical procedure, the determination of the Charge Fingerprint, was performed on a number of key samples.

Following Gillman (1984), it is assumed that the adsorption of  $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$ , and of  $\text{Cl}^-$  onto soil colloid surfaces from a 0.002 M  $\text{CaCl}_2$  solution at various pH values is essentially a measure of *surface negative and positive charge* respectively (Fig. 3.5a). The negative charge, measured by  $\text{Ca}^{2+}$  adsorption, is termed the 'Basic Cation Exchange Capacity' ( $\text{CEC}_\text{B}$ ), and may be determined by the method of Gillman and Sumpter (1986b).

$\text{Ca}^{2+}$  and  $\text{Al}^{3+}$  adsorption is termed the 'Total Cation Exchange Capacity' ( $\text{CEC}_\text{T}$ ), and there is a high correlation between  $\text{CEC}_\text{T}$  at the natural pH of the soil and the 'Effective Cation Exchange Capacity' ( $\text{ECEC}$  = the sum of the basic cations  $\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+ + \text{Na}^+$  and the acidic cations  $\text{Al}^{3+} + \text{H}^+$ ). At low soil pH,  $\text{CEC}_\text{B}$  may be much lower than  $\text{CEC}_\text{T}$  because of the increasing occupation of exchange sites by aluminium (Fig. 3.5 b; Gillman and Sumpter 1986a). Positive charge was measured by  $\text{Cl}^-$  adsorption and termed the 'Anion Exchange Capacity' of the soil ( $\text{AEC}$ ).



**Figure 3.5 Surface charge characteristics and cation and anion exchange capacities of strongly acidic soils ( soil pH < 5). Source: Gillman and Sumpter (1986a)**

**AEC: anion exchange capacity;  $\text{CEC}_\text{T}$ : Total cation exchange capacity measured by the adsorption of  $\text{Ca}^{2+}$  and  $\text{Al}^{3+}$  onto colloid surfaces;  $\text{CEC}_\text{B}$ : Basic cation exchange capacity and measures the ability of the soil to retain those cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ) of interest as important plant nutrients.**

The charge fingerprint analysis is time-consuming, but only needs to be carried out on relatively few samples, in this case on 0 and 50 t/ha Minplus™-ameliorated representatives of each of the seven soils. The charge fingerprint gives a complete picture of the soil cation exchange capacity over the entire pH range of agronomic interest (i.e. pH 4 – 7). It is used to ascertain whether the results of the routine testing are internally consistent, but more importantly it allows modelling of observed changes in routine chemical properties. The conceptual framework it provides will become apparent in the discussion of results below.

### 3.3.4 Results

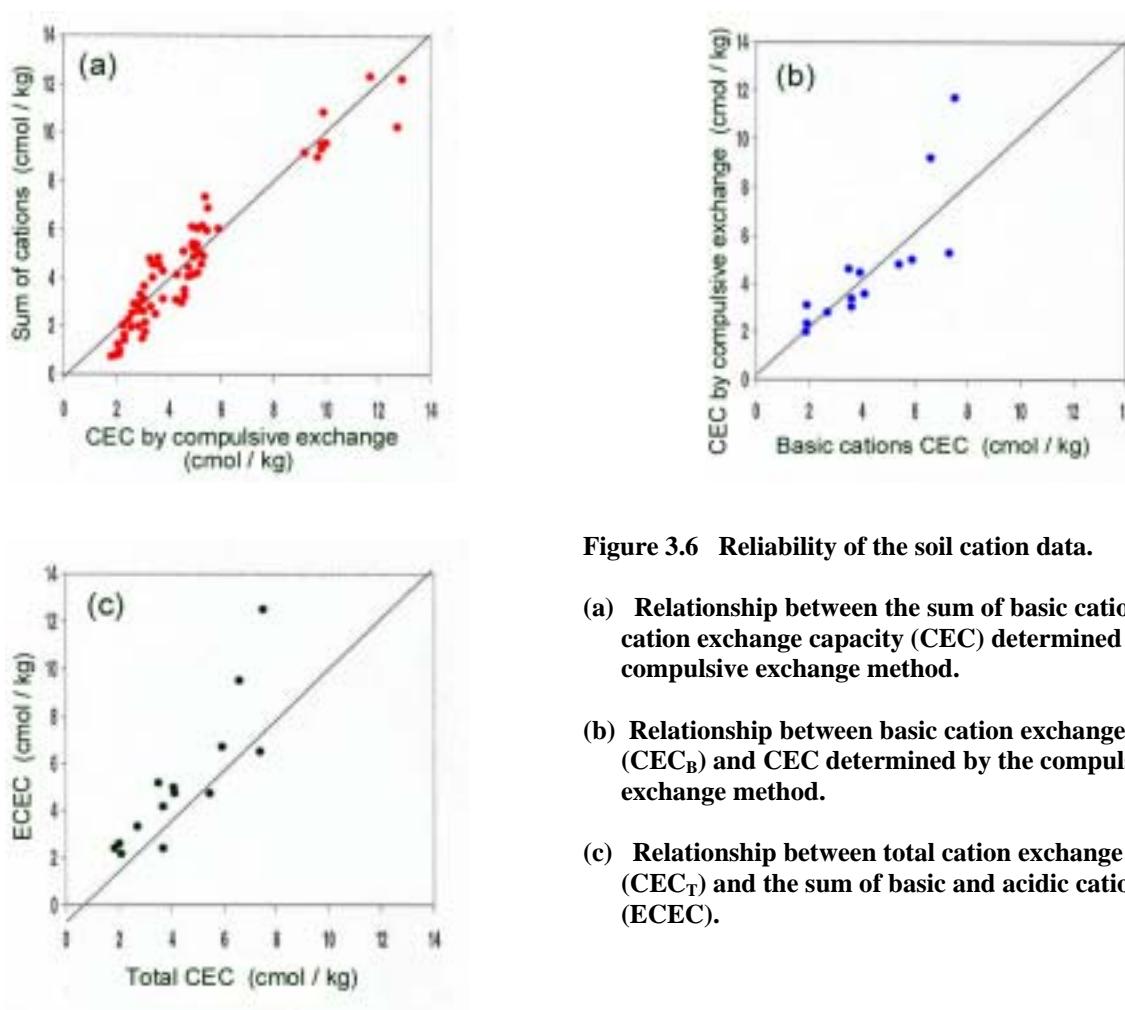
#### *Reliability of the data*

The value of studies relating to soil cation exchange properties is sometimes depreciated when unsuitable methods are used. Therefore, greater confidence in the data, their interpretation, and their predictive value are gained if internal consistency can be demonstrated. To this end, three tests were applied to determine whether or not there were:

- equality between sum of basic cations extracted and the routinely determined soil cation exchange capacity ( $\text{CEC}_\text{CE}$ ; Fig. 3.6 a):

- equality between basic cation exchange capacity ( $CEC_B$ ) estimated from the charge fingerprint, and the routinely determined CEC (Fig. 3.6 b);
- equality between the total cation exchange capacity ( $CEC_T$ ) from the charge fingerprint and the sum of extracted basic and acidic cations. The latter is often designated the Effective Cation Exchange Capacity (ECEC; Fig. 3.6 c).

Figures 3.6 a-c generally show good agreement between the pairs of properties compared, as judged by closeness of the plotted points to the 1:1 line in each case. Two points in each of Figs 3.6 b and c, relating to the Pin Gin soil, indicate that  $CEC_B$  (Fig. 3.6 b) and  $CEC_T$  (Fig. 3.6c) are underestimated.



**Figure 3.6 Reliability of the soil cation data.**

- (a) Relationship between the sum of basic cations and cation exchange capacity (CEC) determined by the compulsive exchange method.
- (b) Relationship between basic cation exchange capacity ( $CEC_B$ ) and CEC determined by the compulsive exchange method.
- (c) Relationship between total cation exchange capacity ( $CEC_T$ ) and the sum of basic and acidic cations (ECEC).

### *The charge fingerprint*

The charge fingerprint illustrates the dependence of CEC on soil pH. By choosing laboratory conditions that approximate field conditions, the curves can be used to predict the effect of management practices on **total CEC**, and the agronomically important **basic CEC**. The latter property indicates the amount of exchangeable basic cations that a soil is capable of retaining in an exchangeable form. In the present study, charge fingerprints were obtained on soil samples to which no Minplus<sup>TM</sup> had been added, and on samples that had received 50 t/ha Minplus<sup>TM</sup>.

Results for the seven soils are summarised in Figs. 3.7 a, b. Minimising the individual fingerprints in this way results in some loss of definition, but it allows an appreciation of any effect of Minplus<sup>TM</sup> addition when fingerprints across a row of figures are compared. Also, by scanning down the left-hand side of the two figures, differences in charge characteristics between the seven untreated soils become apparent.

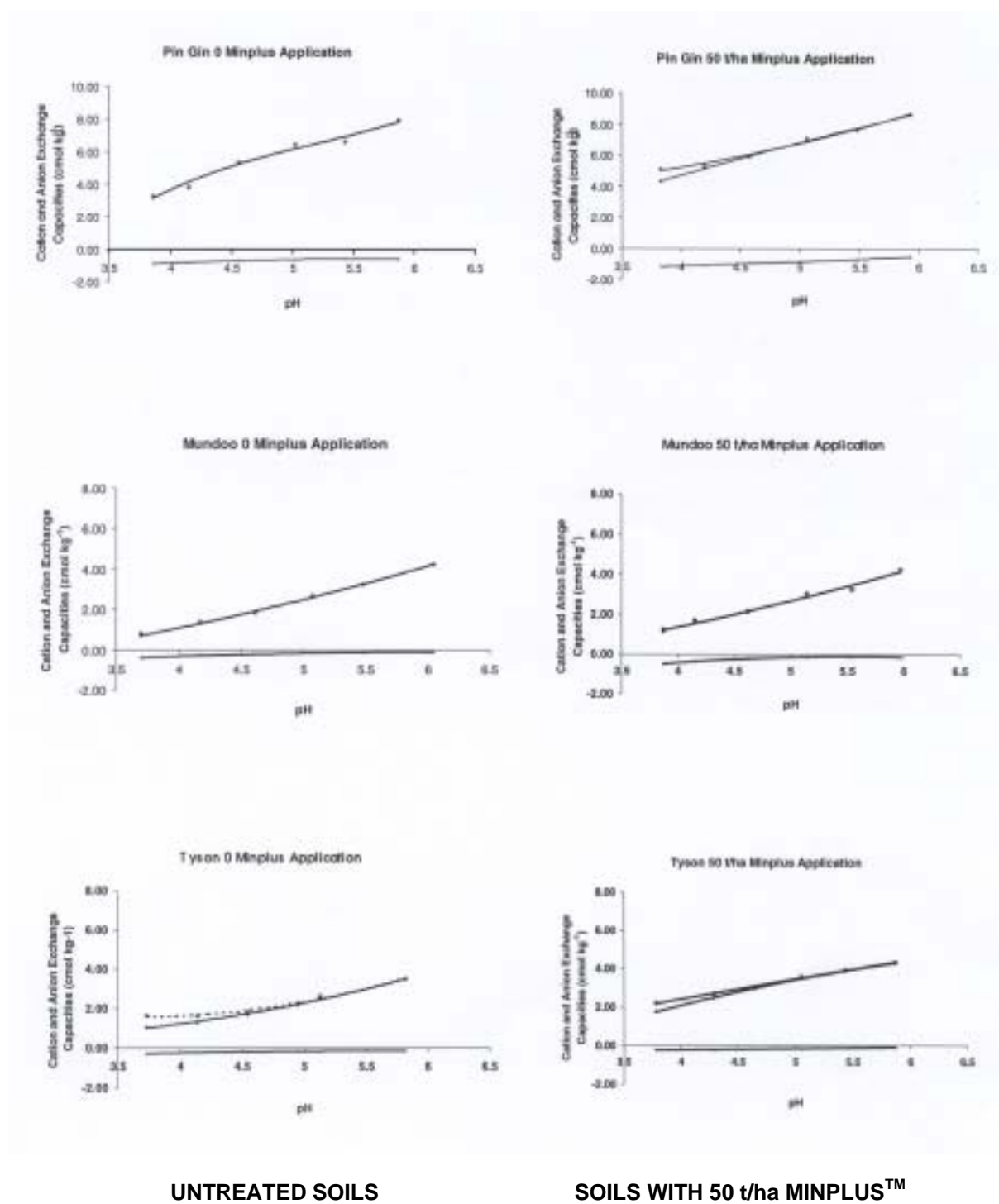


Figure 3.7 a Charge fingerprints for the Pin Gin, Mundoo, and Tyson Soil samples that had been treated with no Minplus™ (left column of diagrams) and 50 t/ha of Minplus™ (right column of diagrams).



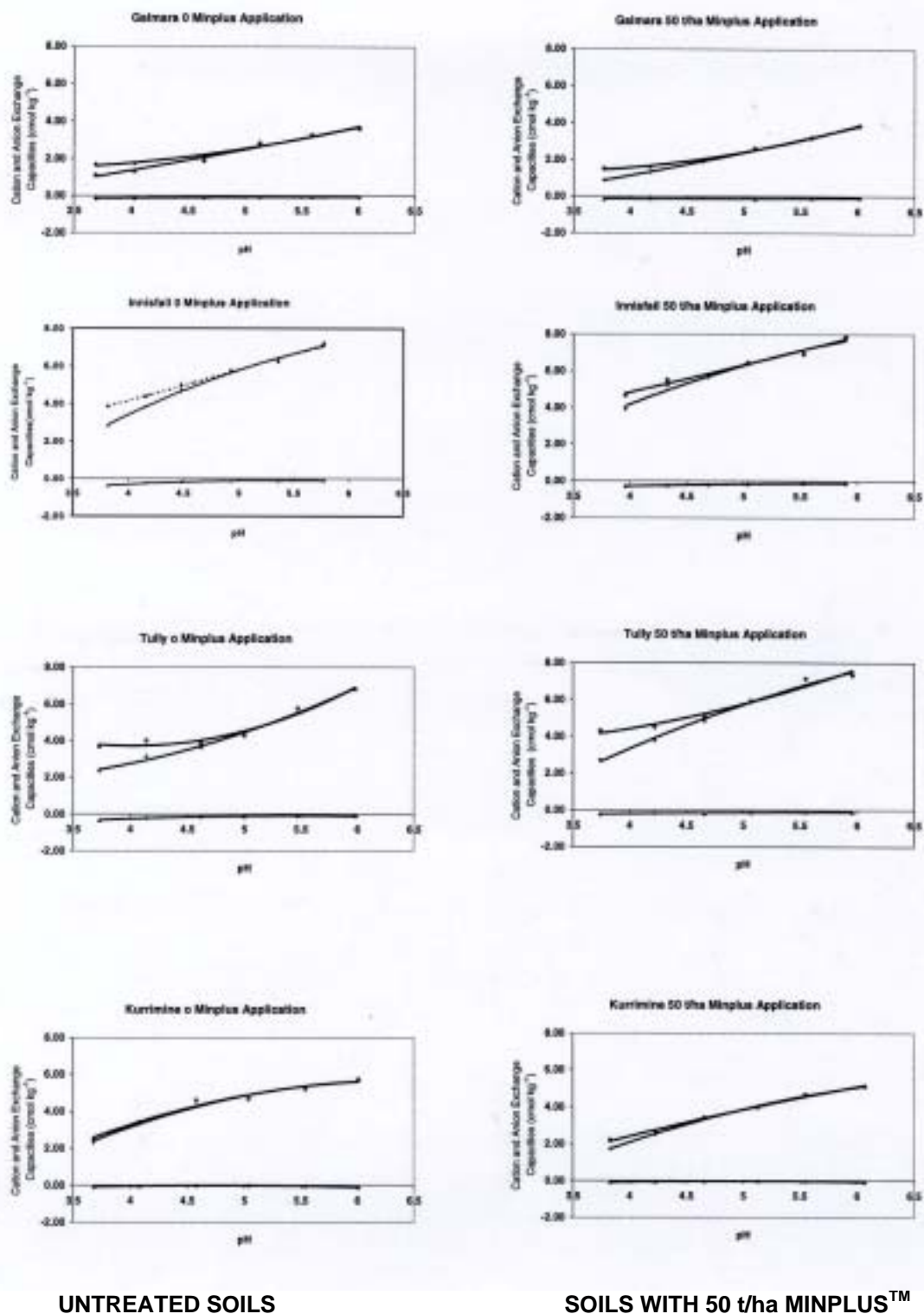


Figure 3.7 b Charge fingerprints for the Galmar, Innisfail, Tully Soils , and the Kurrimine Sand samples that had been treated with no Minplus™ (left column of diagrams) and 50 t/ha of Minplus™ (right column of diagrams).

The charge fingerprint curves can be reduced to equations that allow  $CEC_B$  and  $CEC_T$  to be calculated for any desired soil pH value. Equations for the seven untreated soils are presented in Table 3.3. Using these equations, parameters can be generated to demonstrate differences in surface charge characteristics between the study soils. For instance, Table 3.4 summarises the values for the CEC of the soil at pH 5.5, which illustrates differences in magnitude of charge, and the difference in  $CEC_B$  between soil pH 4 and soil pH 6, which is related to the rate of change of charge with pH.

**Table 3.3 Mathematical relationships between the basic cation exchange capacity ( $CEC_B$ ) and soil pH, and between total cation exchange capacity ( $CEC_T$ ) and soil pH, for each of seven soils from the humid tropical region of north Queensland.**

Soil Series	Charge fingerprint equations
<b>Pin Gin</b>	$CEC_B = -0.390 (pH)^2 + 6.060 (pH) - 14.36$ $CEC_T = -0.390 (pH)^2 + 6.060 (pH) - 14.36$
<b>Mundoo</b>	$CEC_B = 0.127 (pH)^2 + 0.259 (pH) - 1.987$ $CEC_T = 0.127 (pH)^2 + 0.259 (pH) - 1.987$
<b>Tyson</b>	$CEC_B = 0.229 (pH)^2 - 1.014 (pH) + 1.632$ $CEC_T = 0.414 (pH)^2 - 3.023 (pH) + 7.117$
<b>Galmara</b>	$CEC_B = 0.029 (pH)^2 + 0.871 (pH) - 2.586$ $CEC_T = 0.199 (pH)^2 - 1.002 (pH) + 2.684$
<b>Innisfail</b>	$CEC_B = -0.413 (pH)^2 + 6.105 (pH) - 14.418$ $CEC_T = 0.044 (pH)^2 + 1.261 (pH) - 1.590$
<b>Tully</b>	$CEC_B = 0.399 (pH)^2 - 1.894 (pH) + 3.944$ $CEC_T = 0.827 (pH)^2 - 6.637 (pH) - 17.048$
<b>Kurrimine</b>	$CEC_B = -0.463 (pH)^2 + 5.851 (pH) - 12.859$ $CEC_T = -0.408 (pH)^2 + 5.252 (pH) - 11.206$

**Table 3.4 Magnitude of the basic cation exchange capacity ( $CEC_B$ ) at a standardised soil pH (5.5), and the difference in basic cation exchange capacity at pH 4 and pH 6, for each of the seven studied soils from the humid tropical region of north Queensland.**

Soil Series	Basic cation exchange capacity ( $CEC_B$ ) at pH 5.5 (cmol/kg)	Difference in basic cation exchange capacity ( $CEC_B$ ) at pH 4 and pH 6 (cmol/kg)
<b>Pin Gin</b>	7.2	4.4
<b>Mundoo</b>	3.3	3.0
<b>Tyson</b>	3.0	2.6
<b>Galmara</b>	3.1	2.3
<b>Innisfail</b>	6.7	4.2
<b>Tully</b>	5.6	4.1
<b>Kurrimine</b>	5.3	2.5

The seven studied soils have low cation exchange capacities, befitting their designation as highly weathered soils of low inherent fertility. By comparison, a highly fertile, “good agricultural soil” from the Darling Downs area of southeastern Queensland would be expected to have a soil pH of 6.5 – 7.0, and a total CEC of 40 – 60

cmol/kg. Even within the group of studied soils from the humid tropics of north Queensland, there are clear differences in their ability to retain nutrient basic cations, and in the latitude that soil managers have to increase CEC by increasing the soil pH. These issues are explored in more detail in the following Section.

A distinction between  $CEC_B$  and  $CEC_T$  at low pH is not apparent for the Pin Gin and Mundoo Soils, and the Kurrimine Sand, when considering the untreated samples (Figs 3.7 a, b). The other soils exhibit some separation, with the greatest difference between the two CEC determinations seen in the Tully Soil (Fig. 3.7 b). The presence or absence of this effect is almost certainly due to mineralogical differences in the soil clay fraction. It is interesting to note that for two of the former group, the Pin Gin Soil and Kurrimine Sand, a small separation between  $CEC_B$  and  $CEC_T$  appeared following the application of 50 t/ha of Minplus<sup>TM</sup>. It is not clear whether this is an experimental artefact, or whether the mineralogical composition of Minplus<sup>TM</sup> itself has produced the effect observed.

Despite an initial expectation that there might have been enough silicate anions released from the crushed basalt to alter fundamental surface charge characteristics, at least for those soils containing appreciable oxide content, this has not occurred. The charge fingerprints of the Minplus<sup>TM</sup>-treated samples for each soil type are similar to their untreated counterparts. This finding means that any increase in CEC following the application of crushed basalt has to be attributed to an increase in pH, with the amendment acting as a liming agent. It also means that changes in CEC can be predicted from the charge fingerprint of the untreated soil samples

#### *Cation enrichment in soils on different parent materials*

Amounts of basic cations extracted from the incubated soil samples are summarised in Table 3.5. All the studied soils show clear increases in the amounts of nutrient cations Ca, Mg, and K available in an exchangeable form in the soil, but there are appreciable differences between soils:

##### 1. Soils formed on basaltic parent materials

The Pin Gin and Mundoo Soils, although formed on hard basalt rock and basalt-derived sediments respectively, have closely similar morphological characteristics. The Pin Gin Soil selected for this study is from a rainforest site and has never been cultivated. It is amply supplied with basic cations, making the observed increases appear modest (Fig. 3.8 a). On the other hand, the Mundoo Soil has been disturbed by cultivation for some time, and its basic cation content, evidenced by the zero Minplus<sup>TM</sup> treatment, is low (Fig. 3.8 b). A Minplus<sup>TM</sup> addition has produced very acceptable increases in the amounts of exchangeable Ca, Mg, and K in both soils.

##### 2. Soil formed on granitic parent materials

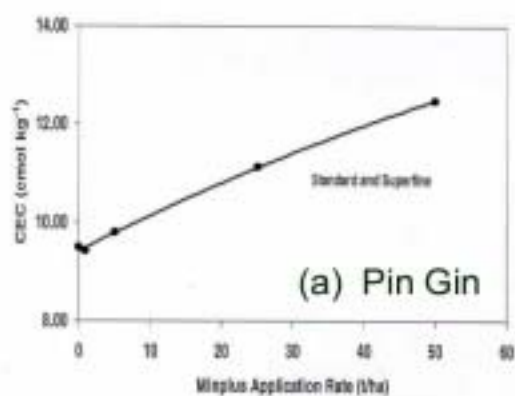
The analysed samples of the Tyson Soil were collected from an undisturbed rainforest location but, even in this virgin condition, contains only modest amounts of exchangeable basic cations. Minplus<sup>TM</sup> application has doubled the amounts of Ca and K, and has produced a four-fold increase in Mg (Fig. 3.8 c). Cultivated granitic soils tend to have even lower amounts of basic cations, so that a crushed basalt application should have a strong ameliorative effect.

##### 3. Soil formed on metamorphic rock

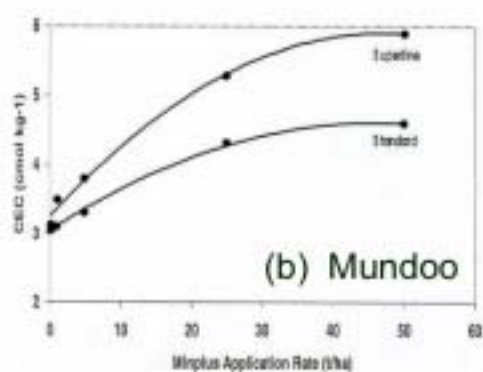
The Galmara Soil is typical of soils formed on a hard rock unit, the Barron River Metamorphics, and these soils generally exhibit very low values for basic cations, with Al dominating the soil exchange complex. The beneficial, ameliorating effects of Minplus<sup>TM</sup> addition have been to greatly reduce Al saturation from over 60% to about 10%, to increase the overall CEC, and to supply significant quantities of exchangeable Ca, Mg, and K (Fig. 3.8 d).

##### 4. Soils formed on stream alluvium

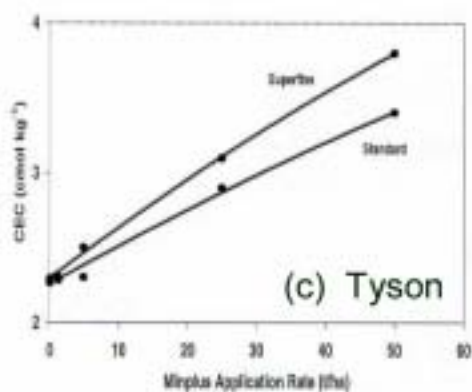
Representing soils formed on river alluvium, the Innisfail and Tully Soils are derived principally from basaltic and granitic materials respectively. The Innisfail Soil, with a basaltic influence on its parent materials, is relatively well supplied with basic cations, and has a high base saturation. The opposite is true for the Tully Soil, which has a strong granitic component in its parent material, and has therefore derived a much greater benefit from the ameliorant (Fig. 3.8 e, f).



Mundoo



Tyson



Galmara

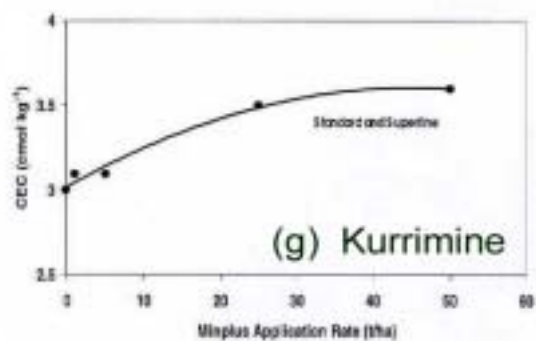
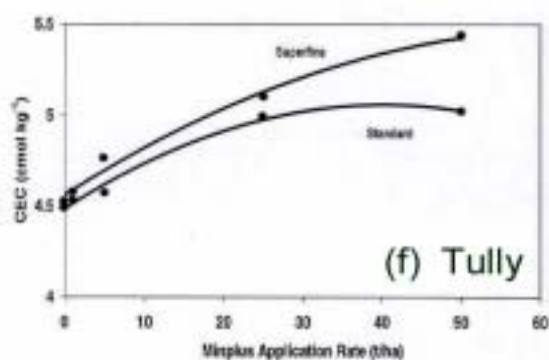
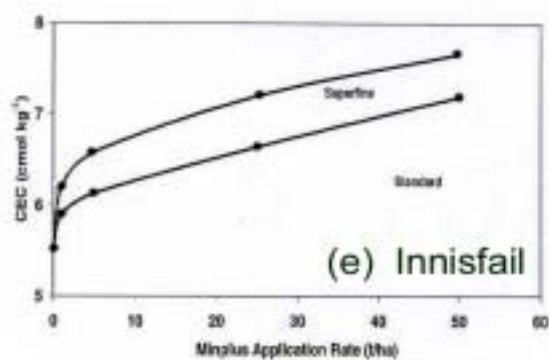
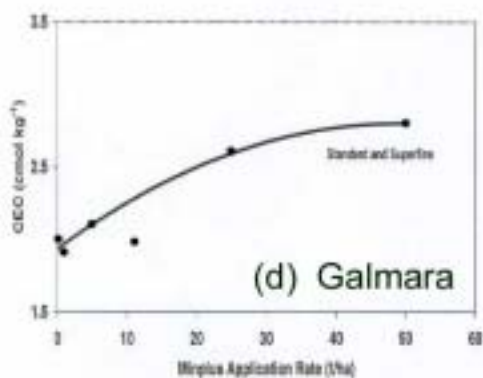


Figure 3.8

Increases in cation exchange capacity produced by increasing rates of application of Minplus™ to the 7 studied soils from the humid tropical Innisfail – Tully area, north Queensland.

#### 5. Soils formed on sandy beach ridges

The Kurrimine Sand has formed from beach sand, has an extremely low clay content, and derives its CEC from limited amounts of soil organic matter in the surface soil. Base saturation tends to be low, but as the soil is weakly buffered, the application of Minplus™ has greatly increased base saturation to about 100% by supplying significant amounts of exchangeable Ca, Mg, and K (Fig. 3.8g).

#### *Value of fine grinding of the rock dust*

Examination of Table 3.5 reveals no additional benefit from this short-term incubation in using Superfine grade Minplus™. This could be a very significant finding, because the production of very finely ground basalt would come at greatly increased cost. Also, the Superfine grade Minplus™ would be much harder to handle in field spreading operations.

#### *Minplus™ as a source of plant nutrients*

Though the units used in this report (cmol/kg) are standard for expressing soil cation contents, a greater understanding of the impact of Minplus™ application is gained if the amounts are converted to kg / ha. On this basis, the amounts of *additional* Ca, Mg, and K supplied by the standard grade Minplus™ are summarised in Table 3.6.

It is abundantly clear that there has been a significant enrichment of basic exchangeable cations from the Minplus™ applications, though this beneficiation is not distributed evenly across the seven soils studied. The increased amounts of nutrient calcium and potassium are very encouraging, while the augmentation of much needed magnesium is outstanding in many cases. The reason for the anomalous values for Pin Gin at low Minplus™ application rate relates to the high native cation content of this virgin rainforest site. Small errors then become magnified by the mathematical treatment used.

**Table 3.5** The effect of Minplus™, applied as Standard (< 250 µm nominal particle size) and Superfine (< 40 µm nominal particle size) grades, on the exchangeable basic cation contents (cmol/kg) of the seven studied soils from the humid tropical region of north Queensland.

Soil and Minplus™ application rates (t/ha)		Exchangeable cation properties of soils treated with Minplus™ applied as Standard grade (< 250 µm)					Exchangeable cation properties of soils treated with Minplus™ applied as Superfine grade (< 40 µm)				
		Ca	Mg	K (cmol/kg)	Na	CEC	Ca	Mg	K (cmol/kg)	Na	CEC
<b>Pin Gin</b>	<b>0</b>	5.26	3.40	0.40	0.11	9.2	5.26	3.40	0.40	0.11	9.2
	<b>1</b>	5.46	3.10	0.39	0.10	9.7	5.20	3.90	0.41	0.07	10.0
	<b>5</b>	5.66	3.20	0.40	0.15	9.8	5.12	3.90	0.38	0.12	9.8
	<b>25</b>	5.62	4.50	0.51	0.23	9.9	5.08	4.50	0.42	0.26	12.7
	<b>50</b>	5.52	5.90	0.58	0.32	11.7	5.42	5.88	0.46	0.45	12.9
<b>Mundoo</b>	<b>0</b>	0.95	1.00	0.11	0.10	3.1	0.95	1.00	0.11	0.10	3.1
	<b>1</b>	1.11	1.24	0.12	0.11	3.1	0.98	1.24	0.15	0.13	3.5
	<b>5</b>	1.12	1.40	0.13	0.12	3.3	1.14	1.68	0.15	0.15	3.8
	<b>25</b>	1.37	2.28	0.23	0.24	4.3	1.63	2.72	0.22	0.32	5.3
	<b>50</b>	1.50	2.88	0.32	0.35	4.6	2.05	3.12	0.29	0.53	5.9
<b>Tyson</b>	<b>0</b>	0.82	0.52	0.15	0.06	2.3	0.82	0.52	0.15	0.06	2.3
	<b>1</b>	0.89	0.56	0.16	0.06	2.3	0.86	0.64	0.14	0.07	2.3
	<b>5</b>	0.98	0.80	0.20	0.10	2.3	0.89	1.08	0.17	0.11	2.5
	<b>25</b>	1.14	1.64	0.25	0.22	2.9	1.21	2.00	0.16	0.26	3.1
	<b>50</b>	1.35	2.04	0.33	0.31	3.4	1.47	2.04	0.38	0.38	3.8
<b>Galmara</b>	<b>0</b>	0.26	0.40	0.06	0.11	2.0	0.26	0.40	0.06	0.11	2.0
	<b>1</b>	0.26	0.40	0.05	0.10	1.9	0.22	0.40	0.05	0.10	1.8
	<b>5</b>	0.32	0.60	0.07	0.10	2.1	0.28	0.72	0.09	0.11	2.1
	<b>25</b>	0.49	1.20	0.15	0.18	2.6	0.57	1.24	0.20	0.50	2.6
	<b>50</b>	0.73	1.64	0.24	0.28	2.8	0.84	1.45	0.26	0.42	2.9
<b>Innisfail</b>	<b>0</b>	2.33	1.60	0.40	0.11	4.8	2.33	1.60	0.40	0.11	4.8
	<b>1</b>	2.08	1.60	0.40	0.12	5.1	2.15	1.48	0.40	0.12	5.0
	<b>5</b>	2.88	1.64	0.40	0.12	5.2	2.17	1.92	0.40	0.16	5.2
	<b>25</b>	2.44	2.28	0.47	0.24	5.1	2.49	2.64	0.51	0.34	5.5
	<b>50</b>	2.59	2.64	0.54	0.37	5.3	2.76	3.12	0.60	0.46	5.5
<b>Tully</b>	<b>0</b>	1.63	1.20	0.12	0.04	4.5	1.63	1.20	0.12	0.04	4.5
	<b>1</b>	1.68	1.20	0.12	0.04	4.5	1.69	1.44	0.1	0.06	4.6
	<b>5</b>	1.66	1.60	0.13	0.04	4.6	1.74	2.08	0.16	0.07	4.8
	<b>25</b>	1.90	2.80	0.20	0.06	5.0	2.12	3.60	0.24	0.11	5.1
	<b>50</b>	2.15	3.52	0.25	0.18	5.0	2.43	4.40	0.33	0.20	5.4
<b>Kurrimine</b>	<b>0</b>	0.83	0.56	0.06	0.07	3.0	0.83	0.56	0.06	0.07	3.0
	<b>1</b>	0.93	0.72	0.05	0.08	3.1	1.20	0.64	0.07	0.08	2.9
	<b>5</b>	1.75	1.16	0.07	0.10	3.1	1.20	1.28	0.09	0.10	2.9
	<b>25</b>	1.75	2.44	0.17	0.19	3.5	1.49	2.60	0.20	0.26	3.4
	<b>50</b>	1.66	2.60	0.24	0.28	3.6	1.58	2.44	0.28	0.43	3.3

**Table 3.6** Additional amounts of basic cations, expressed in kg/ha, supplied in a plant available form by Standard grade (< 250 m) Minplus™ applications to the seven studied soils from the humid tropical region of north Queensland.

Soil	Minplus™ application rates (t/ha)	Exchangeable cation contents (kg / ha)		
		Ca	Mg	K
Pin Gin	1	40	- 36	- 4
	5	80	- 24	0
	25	72	132	43
	50	52	300	70
Mundoo	1	32	29	4
	5	34	48	8
	25	84	154	47
	50	110	226	82
Tyson	1	14	5	4
	5	32	34	20
	25	64	134	39
	50	106	182	70
Galmara	1	0	0	- 4
	5	12	0	4
	25	46	48	70
	50	94	48	70
Innisfail	1	-50	0	0
	5	110	5	0
	25	22	82	27
	50	52	125	55
Tully	1	10	0	0
	5	6	48	4
	25	554	192	31
	50	104	278	51
Kurrimine	1	20	19	- 4
	5	184	72	4
	25	184	226	43
	50	166	245	70

#### *Treatment Longevity*

In this initial study, the soils had been incubated for 3 months with Minplus™ in a moist condition. This type of experiment provides information about the reactivity of Minplus™ with different soils, but does not give any indication on how long lasting the observed effects might be. Additional studies to assess the effects of leaching on Minplus™-treated soils, and the duration of the soil conditioning processes, are reported below (Chapter 8).

Some estimate of long-term benefits can be gained, however, by relating the increase in exchangeable cations observed to the total amounts of elements applied. One tonne of Minplus™ contains about 64 kg of Ca, 63 kg of Mg, and 11 kg of K. These values have been used to calculate the percentages of these elements that have appeared as soil exchangeable basic cations, and results are reported in Table 3.7.

There are obvious discrepancies in the results for the Pin Gin Soil in this data set, owing to the exaggerated effect that this mathematical amplification can have on small analytical error. The trends, however, are clear. The amounts of additional plant nutrient, as a percentage of what was applied, are low, except perhaps at the lowest Minplus™ rate. At Minplus™ application rates of 5 t/ha or more, as much as 70-80% of the nutrient applied is still in reserve. If these reserves become exchangeable over time, as incumbent ions on the exchange

complex are taken up by plants, then application rates at the lower end of the scale could be effective for some considerable time.

**Table 3.7 The contents of exchangeable basic cations of agronomic importance, expressed as percentages of the total amounts of each element applied as Standard grade (< 250 m) and Superfine grade (< 40 m) Minplus™, to the seven studied soils from the humid tropical region of north Queensland.**

Soil	Element	Percentages of elements determined in soils treated with Standard grade (< 250 m) Minplus™				Percentages of elements determined in soils treated with Superfine grade (< 40 m) Minplus™			
		Minplus™ application rates (t/ha)				Minplus™ application rates (t/ha)			
		1	5	25	50	1	5	25	50
Pin Gin	Ca	63	25	5	2	- 19	- 9	- 2	1
	Mg	57	- 8	8	10	95	19	8	9
	K	- 35	0	16	13	35	- 14	3	4
Mundoo	Ca	50	11	5	3	9	12	9	7
	Mg	46	15	10	7	46	26	13	8
	K	35	14	17	15	142	28	16	13
Tyson	Ca	22	10	4	3	13	4	5	4
	Mg	8	11	9	6	23	21	11	6
	K	35	35	14	13	- 35	14	1	16
Galmara	Ca	0	4	3	3	- 13	1	4	4
	Mg	0	8	6	5	0	12	6	4
	K	- 35	7	13	13	- 35	21	20	14
Innisfail	Ca	- 78	34	1	2	- 56	- 10	2	3
	Mg	0	2	5	4	34	24	10	7
	K	0	0	10	10	0	0	16	14
Tully	Ca	16	2	3	3	19	7	6	5
	Mg	0	15	12	9	46	34	18	12
	K	0	7	11	9	0	28	17	15
Kurrimine	Ca	31	58	12	5	116	23	8	5
	Mg	30	23	14	8	15	27	16	7
	K	- 35	7	16	13	35	21	20	16

## 3.4 Phosphorus chemistry of Minplus™-treated soils

### 3.4.1 Introduction

Problems related to the capacity for soils to provide phosphorus (P) to plants have been amongst the most heavily researched issues in soil chemistry. After nitrogen, phosphorus is the element most needed in the majority of soil fertilisation programs, and it normally has to be applied in quantities that far exceed what is known to be required by plants. This is because the bulk of soluble phosphorus added to soil becomes bound to soil particle surfaces so strongly that plant roots are unable to compete for this phosphorus that has become 'fixed'. The removal of soluble P by soil binding mechanisms is termed 'phosphate sorption', or 'phosphorus fixation', and has been the subject of intensive research.

There are many types of chemical reactions that contribute to phosphate sorption, and those exerting most influence will depend on soil type. In humid tropical regions, for instance, the composition of the colloidal fraction of the soil is commonly dominated by kaolinitic clay minerals, and the oxides and oxyhydroxides of iron and aluminium (e.g. hematite [Fe<sub>2</sub>O<sub>3</sub>], goethite [FeO(OH)], gibbsite [Al(OH)<sub>3</sub>], boehmite [AlO(OH)], diaspor



[ $\text{HAlO}_2$ ]). These species react strongly with phosphate, removing it from the soil solution, imparting to the soil a high phosphate sorption capacity.

In red basaltic soils, as much as 10 tonnes of single superphosphate per hectare might be required to quench phosphate sorption before plant requirements can be fully satisfied. On the other hand, the compromise between cost of the purchasing and spreading of fertiliser and the perceived plant responses result in many farmers of the Innisfail – Tully area applying the order of only 250 kg / ha (2 bags to the acre) of superphosphate. Some of this discrepancy may be explained by past phosphatic fertiliser applications having satisfied some of the phosphate sorption capacity of the soil, as suggested by Toreu *et al.* (1988).

Certain chemical species other than phosphate have an affinity for sites that sorb phosphate. These include organic anions released during microbial breakdown of soil organic matter, and inorganic anions that have similar morphology to the phosphate anion, particularly silicate anions. Hence, soils with high soil organic matter contents have lower phosphate sorption capacities compared to their counterparts where organic matter levels have declined. Applications of soluble silicates to soils with high oxide contents have been shown to decrease the phosphorus sorption capacity of the soil.

### 3.4.2 Phosphorus fixation capacity of soils: Theoretical background

Brady and Weil (1996, p.566) have shown that most mineral soils have a large capacity to remove phosphorus ions from soil solution and lock them ('fix') them onto particle surfaces, thus making it very difficult for plant roots to obtain sufficient amounts of this essential element. The phosphorus applied in fertilisers is also subject to this process. The phosphorus fixing capacity of the soil is a major determinant of plant growth in many soils, to the extent that only 10 – 15% of the phosphorus fertiliser is likely to be taken up by plants in the year of application (Brady and Weil 1996).

The availability of phosphorus in the soil varies with a number of factors, including the amount of clay, the mineralogy of the clay fraction, soil pH, the time of application of phosphatic fertilisers which determines the length of time that the soil and phosphorus are in contact, aeration and compaction of the soil, soil moisture and temperature, the soil nutrient status, and the ability of the plant to extract phosphorus from the soil (Glendinning 2000).

Chief among these factors are the amount and mineralogy of the clay fraction, and soil pH. The compounds with which phosphorus reacts in the soil are concentrated in the finer soil fractions. Hence, soils with high clay contents will fix more phosphorus than sandy soils. Highly weathered soils containing relatively large amounts of very fine iron and aluminium oxides and hydroxides sometimes with particle sizes so small as to be 'amorphous', and young volcanic ash soils containing amorphous allophanic clays and humus-aluminium complexes, retain or 'fix' more applied phosphorus than other soils. Thus, the soil mineral components responsible for fixing phosphorus are, in order of decreasing extent and degree of fixation (Fox and Searle 1978) as shown:

<b>very fine, amorphous iron, aluminium, and manganese oxides and oxyhydroxides; allophane</b>	<b>&gt;</b>	<b>fine, crystalline iron, aluminium, and manganese oxides and oxyhydroxides</b>	<b>&gt;</b>	<b>carbonate crystals</b>	<b>&gt;</b>	<b>1:1 clay minerals (e.g. kaolinite)</b>	<b>&gt;</b>	<b>2:1 clay minerals (e.g. illite, smectites)</b>	<b>&gt;</b>	<b>quartz = aluminium- free organic matter</b>
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Phosphorus is most readily available in phosphate-fertilised acidic soils, between soil pH of 6.0 and 7.0 (Glendinning 2000). The greatest degree of phosphorus fixation occurs at very low and very high soil pH. In strongly acidic soils (pH less than 5.5), any added phosphorus forms insoluble compounds with iron, aluminium, and manganese. In strongly alkaline soils, the phosphorus forms insoluble compounds with calcium.

The phosphorus fixing capacity of a soil may be determined by shaking a known amount of the soil in weak calcium chloride solutions containing potassium dihydrogen phosphate ( $\text{KH}_2\text{PO}_4$ ) using the phosphate sorption curve method of Rayment and Higginson (1992). After some 17 hours of shaking, an equilibrium is attained between the phosphate in the solution and that sorbed onto soil particle surfaces. The difference between the phosphorus concentrations in the initial and final solutions represents the amount of phosphorus fixed by the soil. If this approach is repeated using a series of solutions with different initial phosphorus concentrations, the results

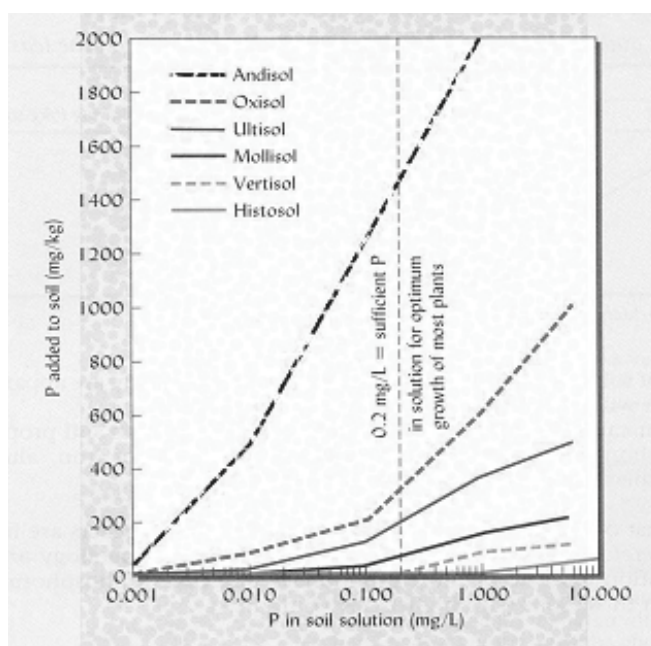
can be plotted as a 'phosphate sorption curve', or a 'phosphate fixation curve', which is characteristic of each soil.

Plants have different requirements for the amount of phosphorus in soil solution to produce near-optimal growth, which is defined as 95% of their maximum yield. Nevertheless, most commercial crops (e.g. corn, cabbage, soybean, tomato, lettuce) require a concentration of 0.1 – 0.2 g of phosphorus / mL, equivalent to 0.1 – 0.2 mg of phosphorus / L, to ensure near-optimal growth (Fox 1981). The amount of phosphorus that is available in the soil to ensure such growth, or that which must be applied in a phosphatic fertiliser, may be determined from the phosphate sorption curve for that soil. Examples of such curves for broad groups of American soils are shown in Fig. 3.9.

Uehara and Gillman (1981) suggested that there are four main reasons why soils differ in their phosphate sorption characteristics:

- differences in the reactivity of the colloid surfaces in the soil, which is dependent on the mineralogy of the fine, colloidal fraction of the soil;
- differences in specific surface area of the minerals comprising the colloidal fraction, which relates to the number of colloidal particles present in the soil in that the finer the particles, the numerous they will be, and the more surface area they will present to soil chemical reactions;
- differences in the capacity of amorphous materials to occlude phosphorus, which is an important process in the Andisols;
- the presence of organic or inorganic ionic species in soil solution that compete with phosphorus for adsorption sites on the colloid surfaces. For example, Roy *et al.* (1971) have demonstrated the capacity for silicate anions from basic slag to reduce phosphate sorption in a range of Hawaiian soils; Uehara and Gillman (1981, their Fig. 3.20) have shown that the organic contents of topsoils of some Queensland soils have produced much lower phosphate fixation capacities than have the associated subsoils.

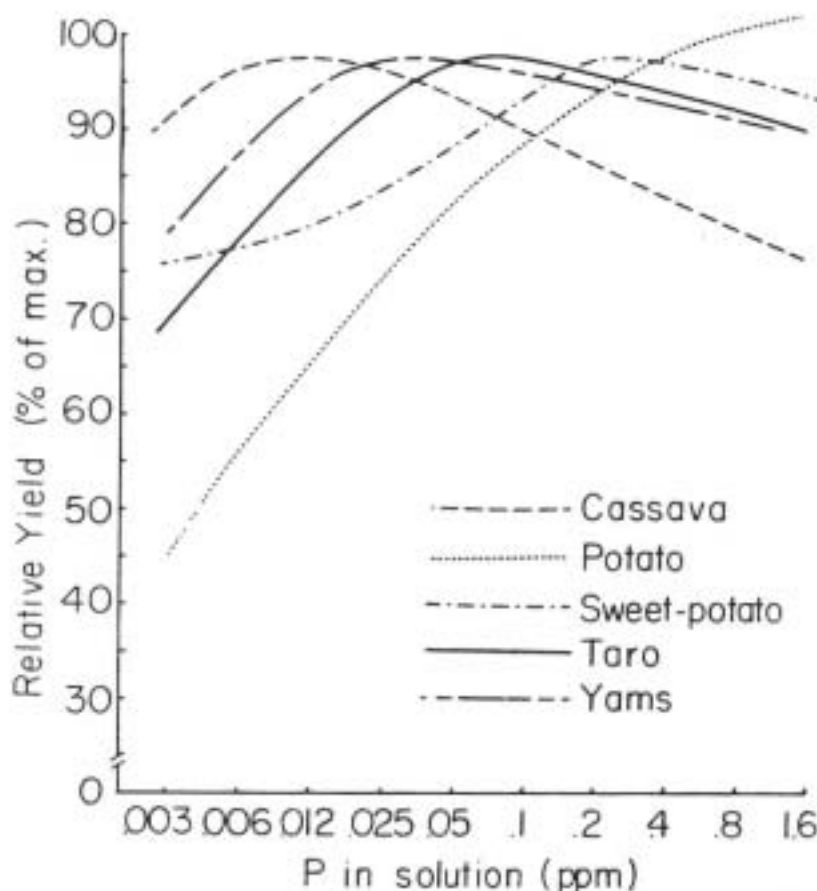
Hence, soils capable of sorbing large amounts of phosphorus are those with large amounts of amorphous oxide minerals such as the young volcanic ash soils, which are classified as Andisols by the US Soil Survey Staff (1975). The Andisols are rare in the world and do not occur in Australia. The other strongly phosphate-fixing soils are those with abundant hydrous oxides of iron and aluminium (i.e. the highly weathered soils of the humid tropics such as the Oxisols or Ultisols. On the other hand, soils with high organic matter contents such as the Mollisols and Histosols, exhibit low phosphate fixation capacities, as was found also by Toreu *et al.* (1988) across a range of soils from coastal north Queensland.



**Figure 3.9** Phosphate fixation curves for several groups defined by the US Soil Survey Staff (1975). The Oxisols and Ultisols represent infertile soils similar to many of the highly weathered soils found in humid tropical regions of north Queensland. The Andisols are young volcanic ash soils, which have a very limited distribution in the world. The Mollisols are the deep, fertile soils of the corn belt of mid-western USA, the Vertisols are the cracking clay soils, and the Histosols are the organic-rich, peat-like soils of wetter areas.

Source: Brady and Weil (1999, p. 566).

The phosphate sorption curve provides a means of predicting how much soluble phosphorus has to be added to a soil to achieve a certain concentration in solution after equilibrium has been established. It has been shown that different crops require different levels of phosphorus in soil solution in order to grow optimally (Fig. 3.10).



**Figure 3.10** The effect of phosphorus in the soil solution on the relative yields of five root crops. Optimal yields of cassava and yams occur at very low levels of phosphorus in the soil solution; other crops such as the Irish potato have a large phosphorus requirement for a good yield. Source: Uehara and Gillman (1981, p.78).

### 3.4.3 Phosphorus fixation capacity of soils: experimental approach

#### *Phosphate Sorption Capacity*

Samples of the seven studied soils from the Innisfail - Tully area (Table 3.1) that had been incubated separately with 0, 1, 5, 25, and 50 t/ha of both Standard grade Minplus™ (< 250  $\mu$ m nominal particle size) and Superfine grade Minplus™ (< 40  $\mu$ m nominal particle size) were used to construct phosphate sorption curves (Fig. 3.11).

Using these curves, it was then possible to rank the seven soils in terms of their phosphate fixing capacity, given that near-optimal plant growth will be attained when the equilibrium concentration of phosphorous in soil solution is of the order of 0.1 – 0.2  $\mu$ g / mL. Such values are listed in Table 3.8.

#### *Available phosphorus*

Phosphorus is an essential element for plant growth and the total phosphorus content of most Australian soils is low. Not only is the availability of phosphorus to plants limited by low total contents in the soil, but also by the form in which the phosphorus occurs, and the phosphate sorption properties of the soil. Numerous soil tests are used throughout Australia to assess the availability of soil phosphorus, and the 14 commonly used techniques have been summarised by Moody and Bolland (1999).

In the present study, the amount of phosphorus solubilised by a weak acid (0.005M H<sub>2</sub>SO<sub>4</sub>) extractant has been used as an indicator of whether a particular soil will respond to applications of phosphatic fertiliser. The analytical method was developed in the Queensland Bureau of Sugar Experiment Stations by Kerr and von Stieglitz (1938). It has been particularly successful in the sugar industry of northern Australia where levels of extractable phosphorus, evaluated by this method, are a useful guide for the fertilisation of plant and ratoon cane.

### 3.4.4 Phosphorus fixation capacity of soils: results

#### *Phosphate sorption capacity of the untreated soils*

Phosphate fixation curves for 6 of the soils studied in the Innisfail – Tully area are shown by the '0 t/ha' lines in Fig. 3.11, which also display curves for the soils that had been incubated with Minplus™ applications at rates equivalent to 1, 5, 25, and 50 t/ha. Because of the very high sand and low clay contents of the Kurrimine Sand (Table 3.1), it offers few colloidal surfaces that are necessary for the sorption of phosphate. Hence, it was omitted from the phosphate fixation analyses.

The soils with high clay contents derived from basalt (Pin Gin Soil), or with a strong basaltic influence on their parent material (Mundoo Soil) have the highest phosphorus fixing capacities. These soils have the highest amounts of extractable free iron, reflecting their basaltic parentage, and significant amounts of aluminium-enriched sites on the mineral surfaces of the relatively abundant kaolinite [Al<sub>4</sub>(Si<sub>4</sub>O<sub>10</sub>)(OH)<sub>8</sub>] or gibbsite [Al(OH)<sub>3</sub>], which reflects the strong weathering conditions that have been imposed on the soil. The edges of kaolinite crystals present abundant reactive surfaces which sorb anions in a manner similar to aluminium and iron oxides (Mattingly 1975), and have a strong affinity for multi-charged anions such as phosphate (Juo 1981).

Perhaps the greatest difference between the Pin Gin and Mundoo Soils is the much higher organic matter content of the former (Table 3.8), which acts to reduce the phosphate fixing capacity of the soil (Toreu *et al.* 1988). This may well explain why the Mundoo Soil, which is closely similar to the Pin Gin Soil in other chemical properties, yielded the highest phosphorus fixation results of the present study. Other phosphate fixation responses to soil organic matter contents have been discussed by Moody and Bolland (1999) who suggested that the relationship depends on the nature of the organic matter and how much iron or aluminium is associated with it.

The soils with somewhat lower clay and free iron contents and formed in mixed alluvial parent materials (Innisfail Soil with a basaltic influence; Tully Soil with a granitic parent material influence) have intermediate phosphorus fixing capacities (Table 3.8). These soils have insignificant aluminium or iron oxyhydroxides evident in their clay fractions and present relatively few sites on mineral surfaces for phosphate sorption.

The soils with the highest sand, lowest clay, and lowest free iron oxide contents (Tyson Soil on granitic alluvium; Galmara Soil on metamorphic rocks) also have the lowest phosphate fixation capacities (Table 3.8). Even though these soils have relatively high amounts of aluminium-rich colloid surfaces present in their kaolinite and gibbsite contents, and iron-rich sites on the surfaces of hematite and/or goethite in their clay fractions, the overall low abundance of clay-sized particles in the soils is insufficient to provide sites that promote significant phosphate sorption.

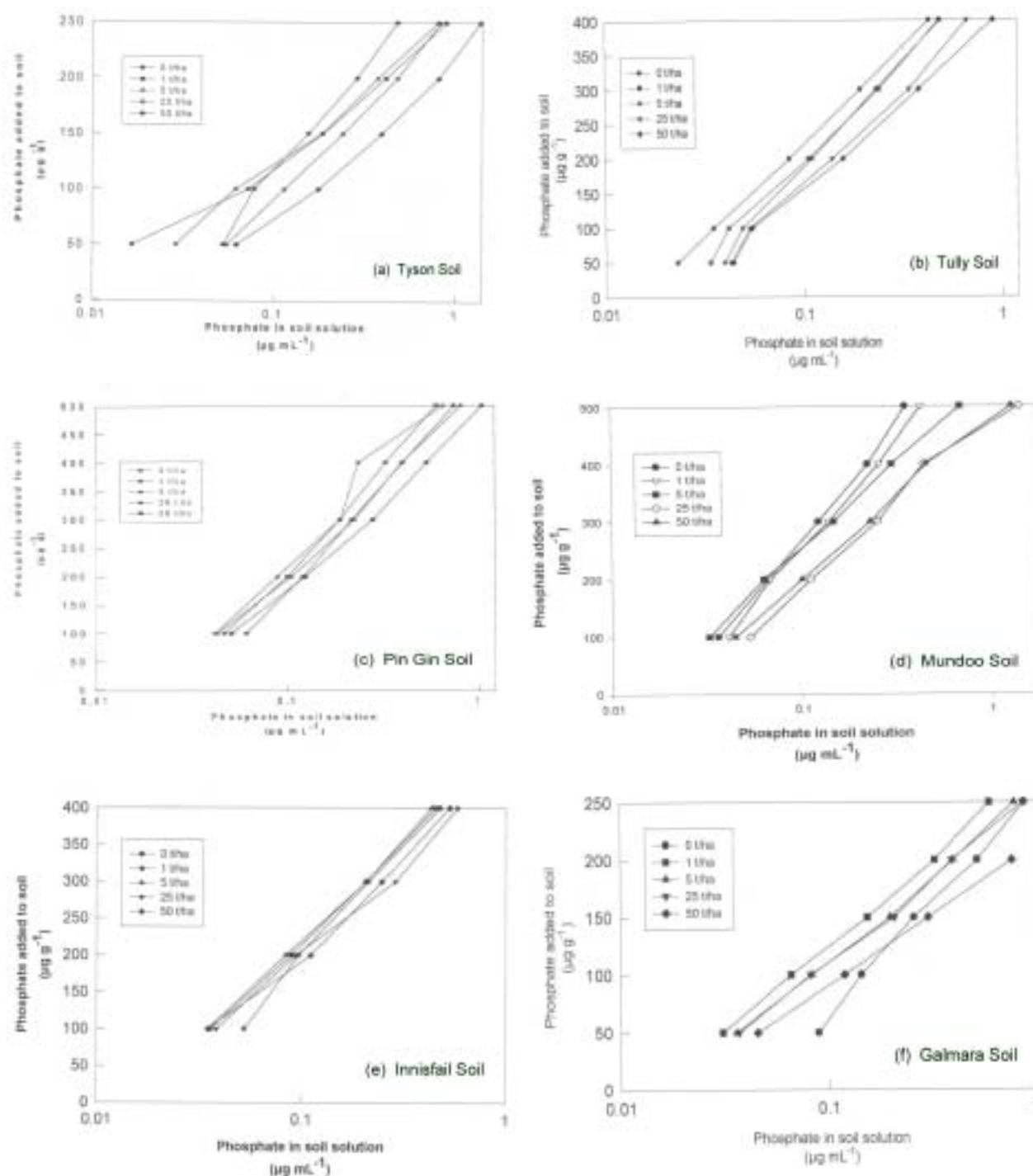


Figure 3.11 Phosphate sorption curves for the 0 – 10 cm layers of 6 soils of the Innisfail – Tully area. The curves represent the phosphate fixing capacities of the untreated soil (0 t/ha), and of soils to which have been applied the equivalents of 1, 5, 25, and 50 t/ha of Minplus<sup>TM</sup>. Source: Burkett (1998).

(a) Tyson Soil Series, (b) Tully Soil Series, (c) Pin Gin Soil Series, (d) Mundoo Soil Series, (e) Innisfail Soil Series, (f) Galmara Soil Series.

**Table 3.8** Selected soil properties, and the amounts of phosphate sorbed by samples of the 0 – 10 cm layers of untreated soils (0 t/ha), and by soils to which have been applied the equivalent of 1, 5, 25, and 50 t/ha of Minplus™. All values in the table are means of 5 replicates per analysis. Sources: Murtha (1986), Gillman and Abel (1987), and Burkett (1998).

Soil Series	Clay content (wt %)	Mineralogy of the clay (< 2 m) fraction	Organic matter (%)	Free ferric oxide (wt %)	Minplus™ application rate (t/ha)	g of P sorbed per g of soil to achieve 0.1 g of P per mL of soil solution	g of P sorbed per g of soil to achieve 0.2 g of P per mL of soil solution
<b>TYSON</b>	20	Kaolin: > 80%	6.3	1	0	113 a	174 a
		Gibbsite: 10-15%			1	130 a	164 a
		Hematite / goethite: 1-5%			5	127 a	165 a
					25	91 b	141 b
		Chloritised vermiculite: 1-5%			50	74 c	116 c
<b>TULLY</b>	40	Kaolinite: 65-80%	6.3	2	0	224 a	306 a
		Illite: 10-20%			1	197 b	283 b
		Chloritised vermiculite: 1-5%			5	186 b	280 b
					25	163 c	247 c
					50	160 c	234 c
<b>PIN GIN</b>	75	Kaolinite: 60-80%	14.5	15	0	178 b	298 c
		Gibbsite: 10-20%			1	213 a	322 a
		Hematite / goethite: 10-20%			5	209 a	304 b
					25	220 a	320 a
					50	180 b	271 c
<b>MUNDOO</b>	41	Kaolinite: 5-10%	8.2	15	0	270 a	385 a
		Gibbsite: 80%			1	253 b	368 a
		Hematite / goethite: 10-20%			5	254 b	347 b
					25	185 c	287 c
					50	202 c	298 c
<b>INNISFAIL</b>	43	Kaolinite: 65-80%	3.4	15	0	188 a	284 b
		Illite: 10-20%			1	217 b	299 a
		Chloritised vermiculite: 10-20%			5	215 b	302 a
					25	193 a	274 b
					50	203 a	281 b
<b>GALMARA</b>	23	Kaolinite: 30-40%	3.9	1.5	0	68 c	125 c
		Gibbsite: 40-50%			1	98 a	129 b
		Hematite / goethite: 5-10%			5	112 a	157a
					25	111 a	155 a
					50	91 b	127 c

**Note:** Mean P sorption values followed by the same letter within a soil group indicate no significant difference ( $p < 0.05$ ).

### 3.4.5 Influence of Minplus™ on phosphate fixation

The data generated from the phosphate sorption curves (Fig. 3.11) have been interpreted only with some difficulty. This is because the relationships between phosphate sorption capacity and Minplus™ applications are not clear in some cases, and have not yielded unambiguous proof that applications of basaltic rock dust result in a reduction in the amounts of phosphorus sorbed onto the different soils. However, some broad trends have emerged which are explained below.

The overall effect of Minplus™ application on phosphorus sorption is perhaps best illustrated in Figs 3.12 and 3.13, where the phosphorus sorption curves for the untreated (zero Minplus™) soils, and those receiving 50 t/ha Minplus™ are presented. Proceeding down the left-hand side of the figure, the differences in sorption capacity between the different soils can be appreciated. This is best done by noting the amount of phosphorus sorbed at a standard solution phosphorus concentration, and 0.2 ppm phosphorus in solution is often used as a standard (Section 3.4.2, above).

Thus the basalt-derived Pin Gin, Mundoo, and Innisfail Soils adsorb about 300 mg of phosphorus per gram of soil when the solution phosphorus concentration is 0.2 ppm (Fig. 3.12); this is brought about by their relatively high contents of iron and aluminium oxide. The Tully Soil adsorbs similar quantities of phosphorus, presumably because of its high exchangeable aluminium content, and moderate concentrations of oxides (Fig. 3.13). The soils on granitic and metamorphic rock parent materials, the Tyson and Galmara Soils, adsorb only half as much phosphorus as the other soils.

The effect of adding 50 t/ha of Minplus™ to each soil is seen by comparing diagrams across the rows of Fig. 3.14. In some cases the effect is modest (e.g. phosphorus sorption in the Innisfail Soil is reduced by about 10%) but is appreciable in others such as the Tyson and Tully Soils, which show reductions of about 35% and 28% respectively. A more comprehensive analysis follows.

Simple linear equations that are about 95% reliable have been fitted to all of the phosphorus sorption curves generated for the six studied soils, at five Minplus™ application rates (0, 1, 5, 25, and 50 t/ha). From these equations (Table 3.9), the phosphorus sorption capacity at 0.2 ppm solution phosphorus has been calculated. These 'standard sorption capacities' have been plotted against Minplus™ application rates in Fig. 3.14. Another equation has been fitted to each of the new plots, to quantify the reductions in phosphate sorption capacity brought about by Minplus™ additions. The  $R^2$  values accompanying each equation indicate how well the linear trends fit the data. It is seen that, in several cases (where the  $R^2$  values are less than about 0.8), interpretation of the plots would have to be treated with caution.

Nevertheless, taken at face value, the intercept term of each equation gives the soil phosphorus sorption capacity without Minplus™ addition (e.g. 298 mg / kg for the Tully Soil), and the slope value for the equation gives the reduction in sorption capacity per tonne of Minplus™ added (e.g. 1.69 mg / kg for the Tully Soil). This means that an application of 50 t/ha Minplus™ causes a reduction in phosphate sorption capacity in the Tully soil of 85 mg / kg (i.e.  $50 \times 1.69$ ), from 298 mg / kg to 213 mg / kg. This equates to a reduction of about 85 kg / ha of phosphorus that would need to be applied to this soil to achieve a soil solution phosphorus concentration of 0.2 ppm phosphorus. In other words, an application of 50 t/ha of Minplus™ to the Tully Soil could mean that 850 kg / ha less of single superphosphate would be needed.

The presumption underlying the reduction in phosphorus sorption capacity following application of Minplus™ is that silicate anions released during Minplus™ dissolution compete with phosphate anions for sorption sites on soil particle surfaces. Discussion of this issue has been postponed, however, until after the results of phosphate extracted from the incubated soil samples have been presented (Section 3.4.6, below).

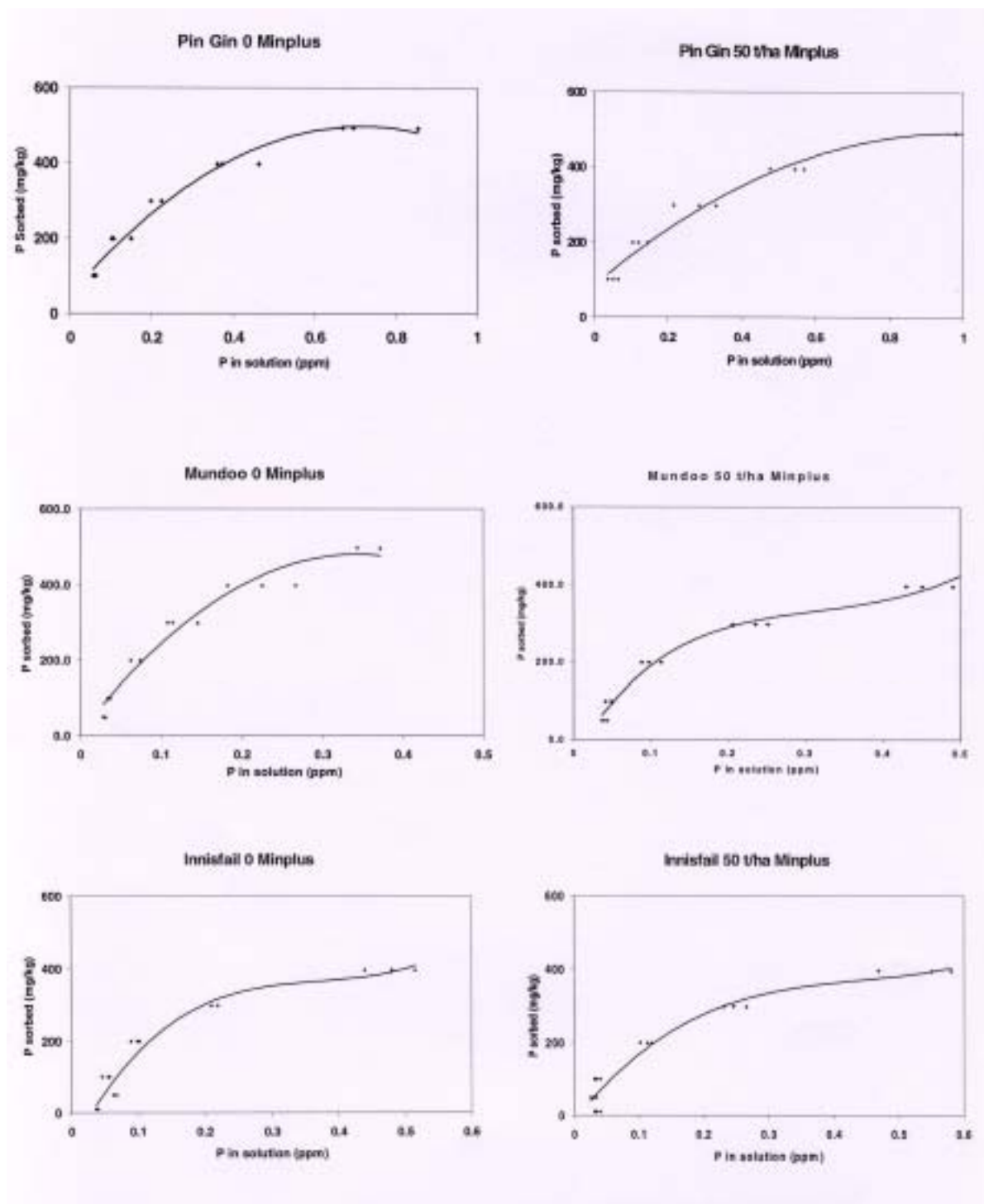


Figure 3.12 Smoothed phosphate sorption curves for the Pin Gin, Mundoo, and Innisfail Soils following incubation with 0 and 50 t/ha applications of Minplus™.



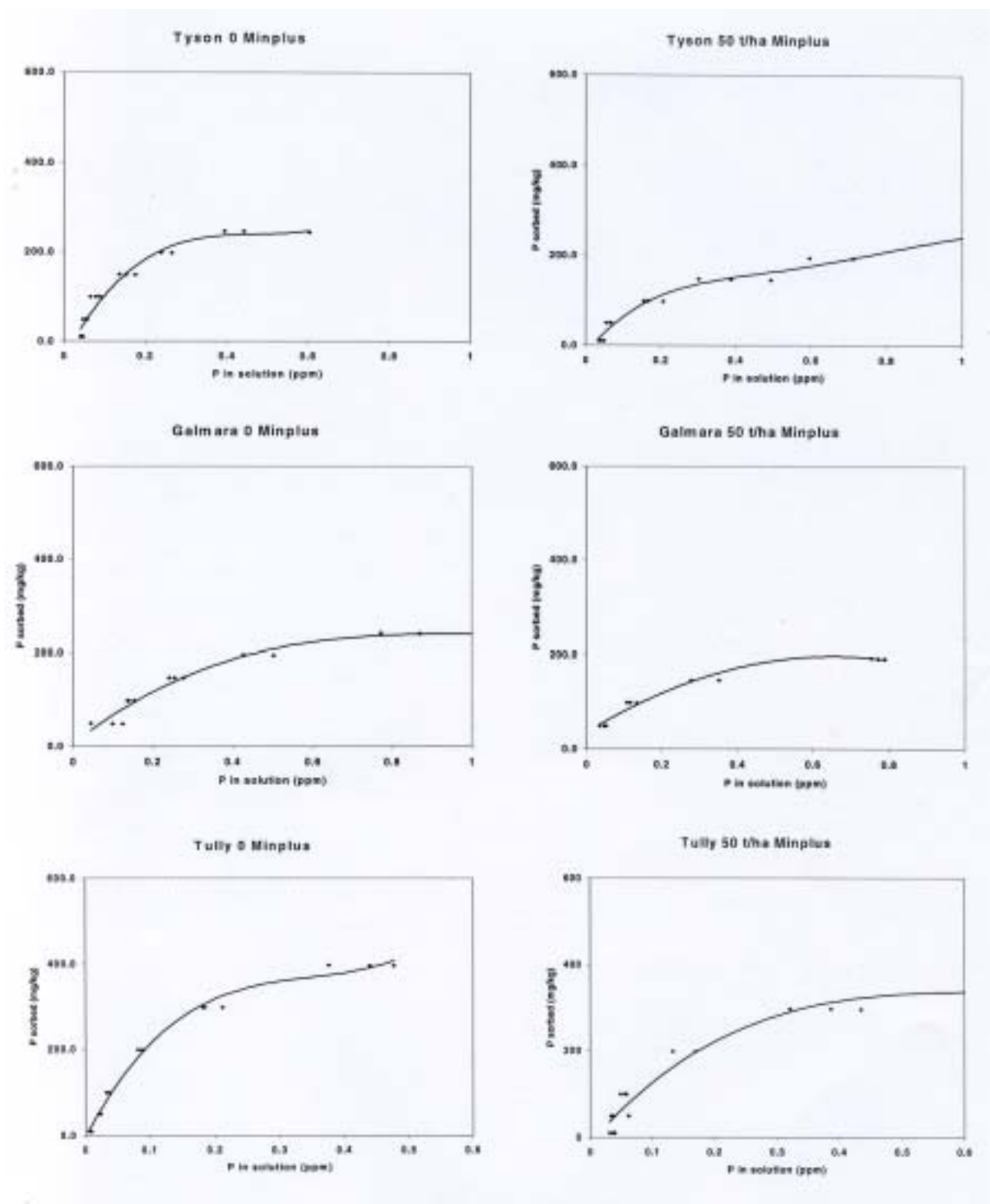


Figure 3.13 Smoothed phosphate sorption curves for the Tyson, Galmara, and Tully Soils following incubation with 0 and 50 t/ha applications of Minplus™. The Kurrimine Sand was omitted because of its low content of soil colloids and its expected low phosphorus sorption capacity.

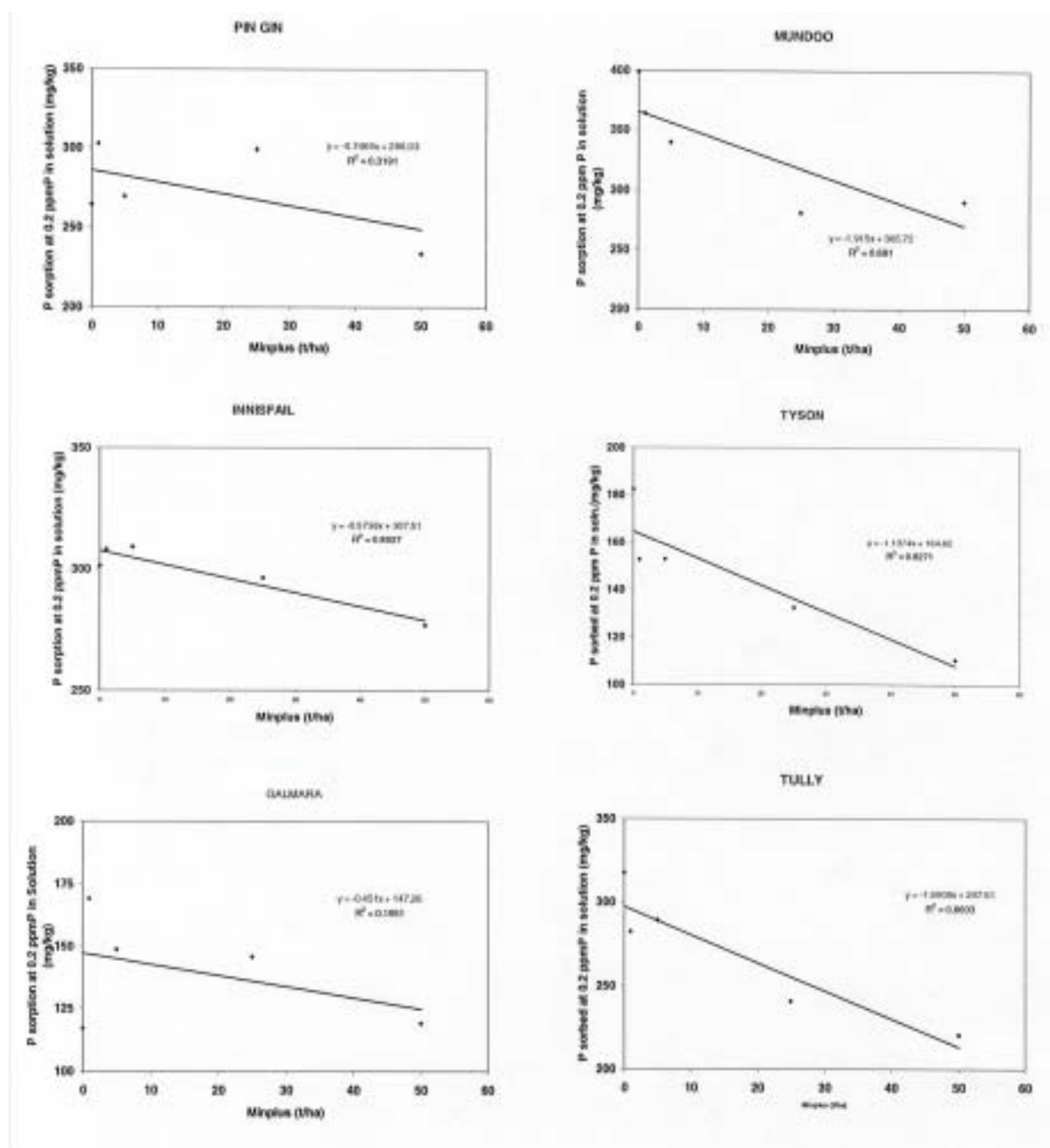


Figure 3.14 Decrease in phosphorus sorption with increasing Minplus™ applications to six studied soils from the humid tropical region of north Queensland. The Kurrimine Sand was omitted because of its low content of soil colloids and its expected low phosphorus sorption capacity.

**Table 3.9 Mathematical relationships between the amount of phosphorus sorbed by the studied soils at 0.2 ppm of phosphorus in soil solution (mg/kg) and the amount of Minplus™ applied to each of seven soils from the humid tropical region of north Queensland.**

Soil Series	Phosphate sorption equations *
Pin Gin	$y = -0.747x + 286.03$
Mundoo	$y = -1.915x + 385.72$
Tyson	$y = -1.137x + 164.62$
Galmara	$y = -0.0451x + 147.26$
Innisfail	$y = -0.574x + 307.51$
Tully	$y = -1.1691x + 297.61$

\*  $y$  = amount of phosphorus sorbed at 0.2 ppm phosphorus in the soil solution

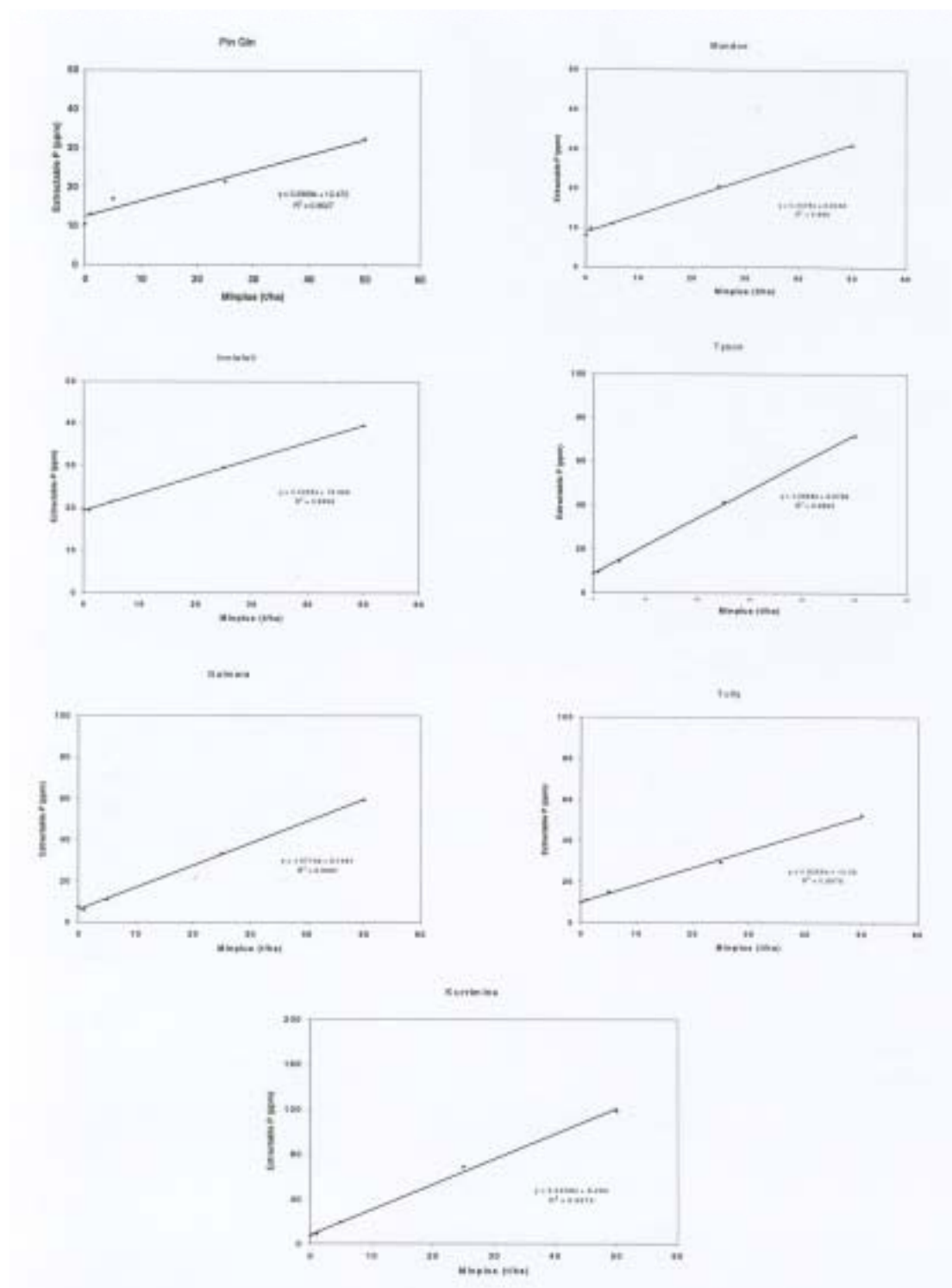
$x$  = rate of application of Minplus™.

### 3.4.6 Influence of Minplus™ on 'plant available' phosphorus

#### *Estimating phosphorus availability in soils*

As mentioned above, the amount of phosphorus that can be extracted with 0.005M H<sub>2</sub>SO<sub>4</sub> is often used as a measure of the fraction of soil P that is readily available for uptake by plant roots. The seven incubated soils of the present study were therefore treated with this extractant to determine whether soil 'available phosphorus', or 'extractable phosphorus' contents were increased by Minplus™ additions. Extractable phosphorus has been plotted against Minplus™ application rate, and the results are shown in Fig. 3.15. This figure includes the soil formed on a beach ridge (Kurrimine Sand) which, because of its expected low phosphorus sorption capacity, was omitted from the sorption study reported in the previous section.

As a rule of thumb, a value of 20 ppm phosphorus obtained by this method can be used as an indicator of phosphate sufficiency in soil. This means that if the extractable phosphorus content of the soil exceeds 20 ppm phosphorus, it is not likely that phosphorus applications would improve plant growth. An examination of Fig. 3.15 shows that all of the untreated soils (with the possible exception of the Innisfail Soil) had extractable phosphorus levels below that critical level before Minplus™ application. Figure 3.15 also shows significant increases in extractable phosphorus values in all of the soils with increasing Minplus™ application rate.



**Figure 3.15** Weak acid (0.005 M sulphuric acid) extractable phosphorus contents of the 7 studied soils of the humid tropical Innisfail – Tully region. The soils have been treated with increasing application rates of Minplus™ (0, 1, 5, 25, 50 t/ha).

In fact, the equations accompanying each curve can reliably predict how much Minplus™ needs to be added to achieve a desired extractable phosphorus level. For instance, to raise the level of available phosphorus in the Tyson Soil to 30 ppm phosphorus, the calculation would use the equation characteristic of the Tyson Soil as follows:

For the Tyson Soil:

$$y = 1.27x + 8.68$$

where  $y$  = Target phosphorus content of the soil (ppm)  
and  $x$  = Minplus™ application rate required.

Hence:

$$30 = 1.27(\text{Minplus}^{\text{TM}} \text{ Rate}) + 8.68$$

Therefore:

$$\text{Minplus}^{\text{TM}} \text{ Rate Required} = (30 - 8.68) / 1.27 = 17 \text{ t/ha.}$$

#### *Source of the available phosphorus*

It is of interest to speculate about the source of this additional extractable phosphorus following incubation with Minplus™. It is not likely that silicate anions dissolved from Minplus™ dissolution would displace phosphate anions from soil sorption sites, when the phosphate anions were not removed with 0.005M H<sub>2</sub>SO<sub>4</sub>. In other words, the additional phosphorus has probably not come from the soil. Rather, it appears that the most likely source of this P is the Minplus™ itself.

Previous analyses have confirmed that the total amount of phosphorus in Minplus™ is about 3000 ppm, or, 0.3% (Table 2.1). This is sufficient to account for the increases in extractable phosphorus observed; an application rate of 50 t/ha Minplus™ would provide an additional 150 ppm of total phosphorus to a soil. It becomes a question of how much of the total phosphorus in Minplus™ can be dissolved by 0.005M H<sub>2</sub>SO<sub>4</sub>. It was found that the solubility of fresh Minplus™ in this extractant was quite low. In fact, only about 50 ppm phosphorus can be extracted. This is less than 2 % of the total amount of phosphorus in the rock dust. Therefore, if Minplus™ is the source of this additional phosphorus following incubation, then there must be a breakdown of the rock dust in the moist conditions prevailing during the relatively short Minplus™ incubation period (3 months), causing a release of phosphorus to the soil solution. This is best exemplified in the Kurrimine Sand, where about 80% of the phosphorus applied in the Minplus™ became available after incubation. As this soil has a very low phosphorus sorbing capacity, the Minplus™-derived phosphorus was easily removed by the H<sub>2</sub>SO<sub>4</sub> extractant.

The percentage of the phosphorus applied in the Minplus™ and extracted by the weak acid treatment is lower for the other six soils, and follows the order:

$$\text{Pin Gin} = \text{Mundoo} = \text{Innisfail} (14\%) < \text{Tully} (28\%) < \text{Galmara} (36\%) < \text{Tyson} (42\%)$$

The sequence roughly corresponds to the reverse of their phosphate sorption capacities (Table 3.8). It could be concluded, therefore, that the phosphorus released from Minplus™ is then sorbed by the soil according to each of the soils' P sorption capacity.

It appears that the application of Minplus™ in sufficient quantities, taking Fig. 3.15 as a guide, could provide enough 'available phosphorus' for plant growth in the short term. Unlike calcium and magnesium, however, the reserves of phosphorus derived from Minplus™ applications would be very limited, a maximum of 3 kg phosphorus / ha for each tonne of Minplus™ applied per hectare. Therefore, it would not be reasonable to rely on Minplus™ applications as a long-term source of plant available phosphorus.

#### *Anions controlling reduced phosphate sorption*

Returning to the discussion on the effect of Minplus™ addition on phosphorus sorption capacity (Section 3.4.5, above), it now seems clear that at least some of the observed reduction in phosphate sorption is due to the

occupation of sorption sites by phosphate anions derived from the Minplus™ application, rather than by silicate anions.

The relative contributions of Minplus™-released phosphate and silicate anions to the reduction of phosphate sorption in all of the soils studied cannot be quantified with certainty, because the actual percentages of total phosphorus released to the soil solution from Minplus™ additions to the various soils is not known.

If, however, the dissolution of Minplus™ that occurred in the Kurrimine Sand can be taken as a guide, then approximately 2.5 ppm of phosphorus was released for each tonne of Minplus™ applied. This value is larger than any of the slope values of the equations shown in Fig. 3.14, and would easily account for the reductions in P sorption capacity observed.

Similar results were derived from a pot trial study on an extremely well sorted quartzitic sand from the Cape Flattery Silica Sand Mine, some 450 km north of Innisfail. Details of this study are presented below (Chapter 5).

When phosphatic fertilisers are applied to highly weathered soils to which Minplus™ applications had previously been made, the bulk of the reactive sites on the colloidal surfaces are now occupied by either phosphate or silicate anions that were derived from the Minplus™. Thus, the phosphate anions from the fertiliser are prevented from forming chemical bonds with the iron or aluminium atoms on the surfaces of the colloids. The fertiliser phosphate, therefore, remains in soil solution and remains available for uptake in a soluble form by plant roots.

An increase in plant growth as a consequence of Minplus™ applications reducing the phosphate fixation capacity of highly weathered soils has been demonstrated in field and pot experiments on the Innisfail Soil which are discussed below (Chapters 4 and 6).

## **3.5 Silicon chemistry of Minplus™-treated soils**

### **3.5.1 Introduction**

There are papers in the soils literature that deal with improvements in plant growth that have been induced by the addition of silicon in the form of silicate amendments to both soils and soil-less water culture solutions (see for example: de Villiers 1961, 1962; Fox *et al.* 1967; Chesworth *et al.* 1983, 1985; Barcelo *et al.* 1993; Epstein 1994). It is possible that plants well supplied with available silicon can deposit large amounts of silicates in cell walls, thus making it almost impossible for various fungi to insert their haustoria into the plant cells (Menzies *et al.* 1991). An improved silicate supply in the soil may similarly enhance pest resistance in sugarcane by producing cell walls that are too tough for successful attack by cane grubs (Anonymous 2000).

A high proportion of the silicon [Si] present in basaltic rock is in the form of silicates in the structures of primary minerals. When finely crushed, these rocks have a high abrasion pH (> pH 8), and a proportion of silicon released when the rock dust contacts water should remain in silicate form. Silicate mineral solubility from this source would be low compared to pure sodium silicates or calcium silicates, but enough soluble silicate could be released from crushed basalt to block some phosphate sorption sites, if the finely divided material were mixed with moist soil.

Because of the high content of silicates in Minplus™, and the probable role of silicate ions in helping to alleviate phosphate fixation problems in acidic, highly weathered soils, an attempt was made to determine the content of extractable silicon from Minplus™-treated and untreated soils. Therefore, we have determined the amounts of silicon that can be extracted from the seven incubated soils of the study (Table 3.1) by a variety of extractants. The extractants have been shown by others to indicate silicon sufficiency or deficiency in soils, for crops which appear to require silicon as an essential element to attain near-optimal yields, particularly sugarcane and rice.

### **3.5.2 Experimental approach**

Four extractants have been used in this study to examine the various 'pools' of silicon that might be identified and used to predict silicon deficiency. The effect of Minplus™ addition on these pool levels has also been evaluated.

The silicon extracted with **water** is obviously the most plant-available form of the element, but water would not be expected to remove any silicon bound to soil particle surfaces. Water extraction sometimes results in clay dispersion, making it difficult to obtain clear solutions for silicon analysis. The procedure extracts the most labile form of Si in the soil (primarily monomeric silicic acid) and is similar to the colorimetric method of Page *et al.* (1982). It involves the reaction of silicic acid with molybdic acid to form a silicomolybdous acid complex that is employed in the colorimetric determination process.

The use of **0.1M CaCl<sub>2</sub>** as an extractant is a popular substitute for water only, as clay dispersion is suppressed. The analysis of silicon in the extractant solution is also based on the colorimetric method of Page *et al.* (1982). Two other often-used extractants, **phosphate-acetate buffer** at pH 3.5, and **0.005M H<sub>2</sub>SO<sub>4</sub>**, are thought to remove sorbed silicon. The higher acidity and the presence of strong replacing anions in these two extractants ensure that greater amounts of silicon are removed, compared to the water and CaCl<sub>2</sub> extractants. In a Hawaiian study with rice, the amounts of Si extracted with phosphate-acetate buffer were closely related to the amounts of Si actually removed from the soil by the crop (Fox *et al.* 1967).

The method used to determine soil silicon contents is similar to the weak acid extraction of phosphorus method of Rayment and Higginson 9G1 (1992). The calcium chloride and phosphate – acetate methods extract the silicon as a molybdosilicic acid complex, which is reduced by a sodium bisulphite / anhydrous sodium sulphite / 1-amino-2-hydroxy-naphthalene-4-sulphonic acid solution. The analysis was carried out on soil extracts obtained by the method of Kerr and von Stieglitz (1938) and the amount of extractable silicon determined by an automated colorimetric procedure based on the method of Murphy and Reilly (1962).

### 3.5.3 Silicon extracted from Minplus™-treated soils

The results for silicon extracted by four methods, for the seven studied soils, incubated with a range of application rates of Standard and Superfine grades of Minplus™, are presented in Table 3.10. Each value represents the mean of five separate soil incubations. The reason for condensing these results into a single table is to illustrate a number of general observations:

There are large differences in ‘available silicon’ contents in the seven soils studied.

Amounts of silicon extracted by 0.1M CaCl<sub>2</sub> and by water are lower than those removed by the other extractants; they are thought to represent that fraction that is most plant-available.

Applications of Minplus™ result in increasing amounts of silicon extracted by all of the extracting solutions.

The Superfine grade (< 40 µm) of Minplus™ generally produced greater amounts of extractable silicon than the Standard grade (< 250 µm) of Minplus™.

The amounts of silicon extracted with 0.005M H<sub>2</sub>SO<sub>4</sub> was considerably higher than that extracted by the other extractants.

#### *CaCl<sub>2</sub> extractable silicon*

Silicon extracted by 0.1M CaCl<sub>2</sub> has been increasingly used as a measure of Si immediately available for plant uptake. Its popularity is associated with an absence of clay dispersion during the extracting procedure, leading to clear extracts for Si determination. Limited studies with sugarcane cultivation indicate that little response to silicon application is to be expected if the CaCl<sub>2</sub>-extractable silicon content of the soil is greater than 20 ppm.

The effect of adding Standard grade Minplus™ to the seven studied soils of the study on their CaCl<sub>2</sub>-extractable Si levels is summarised in Fig. 3.16. Based on the above criterion, all of the soils, except for the Innisfail Clay, would appear to be silicon deficient for those crops requiring the element.

The amounts of Minplus™ needed to reach the ‘critical value’ of 20 ppm of silicon in the soil varies with soil type. Applications of 5 – 10 t/ha of Minplus™ is needed on the basalt-derived Pin Gin and Mundoo Soils, about 25 t/ha for the Galmara Soil on metamorphic rock, while the granite-derived Tyson and Tully Soils and the Kurrimine Sand would require more than 50 t/ha Minplus™.

**Table 3.10** Amounts of silicon extracted (ppm) by four different methods from the seven studied soils that had been incubated with increasing application rates of Standard (< 250  $\mu$ m) and Superfine (< 40  $\mu$ m) grades of Minplus<sup>TM</sup>.

Soil and Minplus <sup>TM</sup> application rate (t/ha)		Silicon extracted from soils treated with Standard grade (< 250 $\mu$ m) Minplus <sup>TM</sup>				Silicon extracted from soils treated with Superfine grade (< 40 $\mu$ m) Minplus <sup>TM</sup>			
		Silicon (ppm) extracted by:				Silicon (ppm) extracted by:			
		CaCl <sub>2</sub>	Water	Phosphate– Acetate	H <sub>2</sub> SO <sub>4</sub>	CaCl <sub>2</sub>	Water	Phosphate– Acetate	H <sub>2</sub> SO <sub>4</sub>
Pin Gin	0	16.4	11.9	77.8	155.5	16.4	11.9	77.8	155.5
	1	17.1	13.0	87.9	183.6	17.3	14.7	76.6	210.3
	5	21.3	15.0	113.6	260.0	22.7	16.3	96.5	266.7
	25	32.4	20.6	174.8	765.4	34.7	24.4	231.4	856.6
	50	37.9	25.2	236.7	1233.2	39.6	n.d.	n.d.	1900.4
Mundoo	0	12.5	6.1	38.5	164.6	12.5	6.1	38.5	164.6
	1	13.9	6.8	43.4	187.9	13.7	6.8	49.2	187.6
	5	17.5	8.5	54.1	257.7	22.1	10.0	71.7	277.5
	25	27.8	14.3	104.3	610.8	36.8	16.3	153.2	838.7
	50	32.9	17.4	156.1	1220.4	44.7	20.7	219.1	1476.5
Innisfail	0	26.0	16.4	90.0	232.2	26.0	16.4	90.0	232.2
	1	24.7	16.5	97.5	277.7	18.5	15.2	109.9	312.8
	5	25.4	16.6	112.7	355.0	19.2	17.0	125.9	435.3
	25	28.0	19.2	150.5	734.6	22.4	20.3	182.5	995.6
	50	28.0	20.3	201.0	1195.1	20.3	20.1	233.0	1567.2
Tyson	0	3.0	3.1	18.0	36.5	3.0	3.1	18.0	36.5
	1	3.7	3.7	25.7	66.1	4.4	6.3	27.9	84.9
	5	6.3	5.1	39.3	145.9	8.2	7.9	51.8	193.3
	25	12.6	11.0	70.3	544.6	16.9	11.9	128.1	720.2
	50	16.2	12.9	116.6	1029.4	21.0	14.0	235.2	1649.9
Galmara	0	2.9	2.8	10.7	30.9	2.9	2.8	10.7	30.9
	1	3.4	3.3	16.1	58.0	5.2	3.7	17.9	61.8
	5	8.1	5.3	23.7	131.9	10.3	6.3	35.5	166.7
	25	19.9	8.9	64.5	534.0	20.8	10.8	92.6	760.9
	50	24.6	10.8	94.9	988.7	27.5	13.2	154.4	1577.3
Tully	0	8.1	8.7	30.7	133.8	8.1	8.7	30.7	133.8
	1	7.8	9.9	35.7	157.0	7.2	8.4	36.7	172.6
	5	8.9	10.7	45.8	227.6	8.6	10.8	54.1	278.6
	25	14.3	12.9	86.7	597.7	13.7	16.7	108.1	833.4
	50	17.5	15.8	129.7	1108.9	18.6	21.3	176.6	1627.8
Kurrimine	0	2.2	1.1	12.2	20.4	2.2	1.1	12.2	20.4
	1	3.6	1.9	16.2	23.4	5.0	2.1	17.5	34.5
	5	7.1	3.2	18.2	64.1	7.0	3.3	15.1	82.1
	25	14.2	4.6	26.7	364.7	15.8	6.0	28.0	634.9
	50	16.1	5.6	39.1	829.0	18.9	6.3	n.d.	1270.0



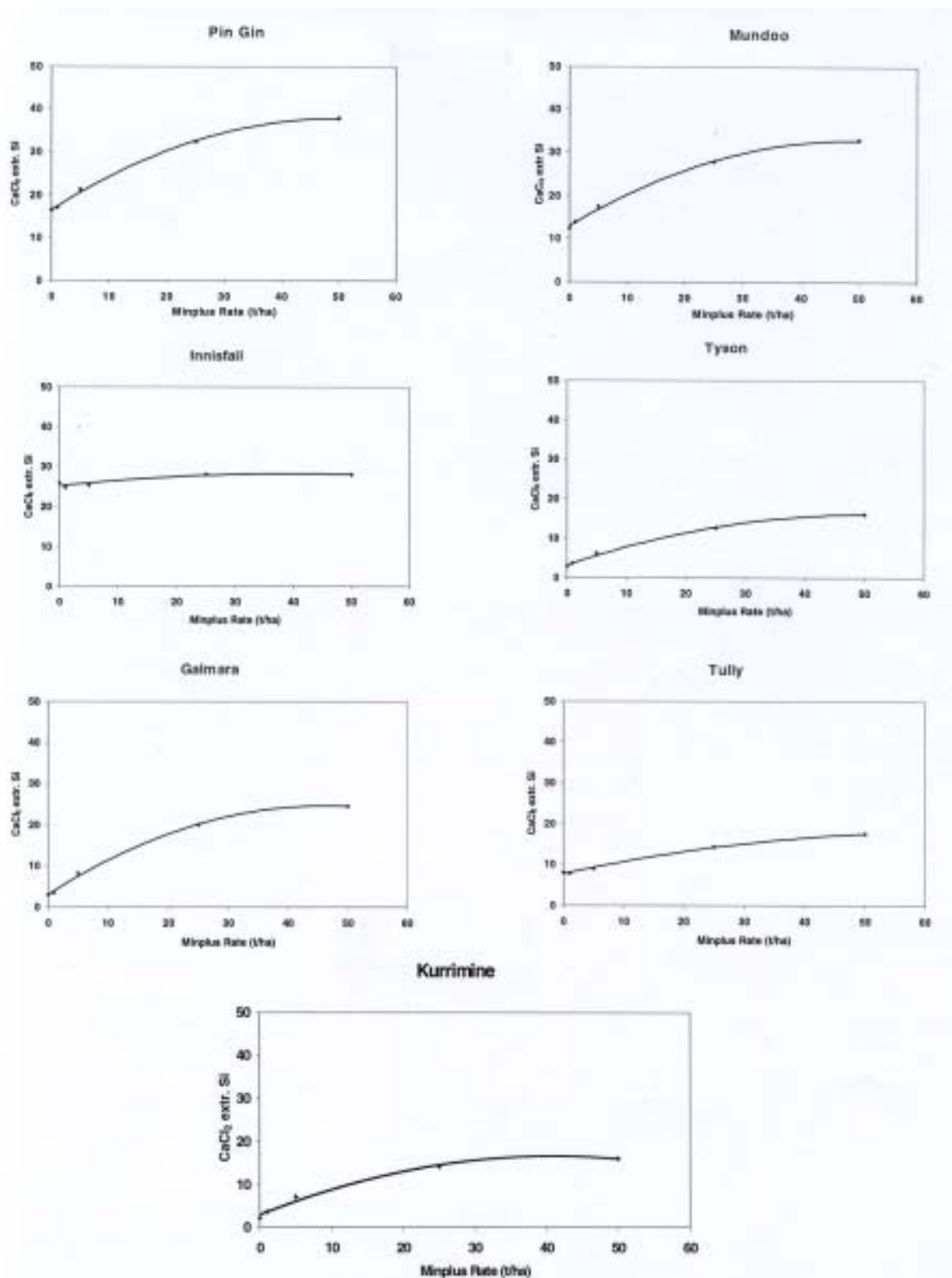


Figure 3.16 Amounts of silicon extracted (ppm) by 0.1 M CaCl<sub>2</sub> with increasing application rates of Minplus<sup>TM</sup> in the seven studied soils from the humid tropical region of north Queensland.

### *Phosphate – Acetate extractable silicon*

Figure 3.17 illustrates the increases in phosphate – acetate-extractable silicon resulting from the addition of Standard grade Minplus™ to the seven studied soils. There is some evidence from work in Hawaii that a ‘critical range’ for estimating the likelihood of Si response using this extractant is 50 – 150 ppm of silicon (Fox *et al.* 1967). This is a rather broad range, but using it again points to the possibility that all of the soils in the study would respond to silicon applications for crops requiring the element, with the Innisfail and Pin Gin Soils falling into the ‘marginal’ category.

The increases in phosphate – acetate-extractable silicon contents in the soil with increasing Minplus™ application are very interesting. At first glance, the increase could be attributed to the solubilisation of unreacted Minplus™ by the extractant, which is buffered at a relatively low pH of 3.5. If this were true, however, we would expect to see a similar rate of increase in extractable silicon with increasing Minplus™ applications to the Kurrimine Sand as is observed in the other soils. That this is not so, indicates that in the other soils, which contain components such as iron and aluminium oxides and exchangeable Al, the reaction of silicon solubilised from Minplus™ promotes further dissolution of silicon from Minplus™. This reaction would proceed at different rates in different soils that contain these reactive components, and would continue until dynamic equilibria are reached. The outcome would be the formation of ‘sorbed Si’ that is available for extraction by the phosphate – acetate buffer.

In fact, assuming that the increase in the unreactive Kurrimine Sand is almost entirely due to the solubilisation of Minplus™, the amount of silicon released per tonne of Minplus™ is 0.5 ppm of silicon. Applying this ‘solubility factor’ to the other soils shown by the dotted lines in Fig. 3.17 shows that, after allowing for solubility, there is still a considerable increase in extractable silicon in the soil. This indicates that Si, probably as silicate, has been adsorbed onto soil surfaces to varying degrees.

Leaving out the Innisfail sample, there is a strong positive correlation between the amounts of silicon extracted from the untreated (0 t/ha) Minplus™ samples and the slopes of the silicon – Minplus™ curves of Fig. 3.17. This implies that the soils with the greater amount of naturally sorbed silicon are able to cause the most sorption of silicon from Minplus™ applications.

The ‘critical range’ of 50-150 ppm silicon for the phosphate – acetate extractant is too broad for determining the amount of Minplus™ required to meet plant demand. Field experimentation would be required to identify a workable ‘critical value’ for phosphate – acetate-extractable silicon in the studied soils.

### *Weak acid extractable Si*

The amounts of silicon extracted with 0.005 M H<sub>2</sub>SO<sub>4</sub> are presented as a function of Minplus™ application in Fig. 3.18. A value of 100 ppm of silicon by this method has been suggested as a critical value (Fox *et al.* 1967), though the evidence is sketchy. If such a value were used in the present study, it would suggest that only three of the soils would respond to silicon applications, namely the Tyson and Galmara Soils, and the Kurrimine Sand.

Using the same approach as for the phosphate – acetate extractant discussed in the previous section, the amounts of silicon removed from the Kurrimine Sand by the H<sub>2</sub>SO<sub>4</sub> extractant were assumed to be due to Minplus™ solubilisation; a ‘solubility factor’ of 16 ppm silicon per tonne of Minplus™ applied was calculated. Deducting this ‘soluble Si’ from the curves in Fig. 3.18 yields the curves (dotted lines) for sorbed silicon resulting from Minplus™ application.

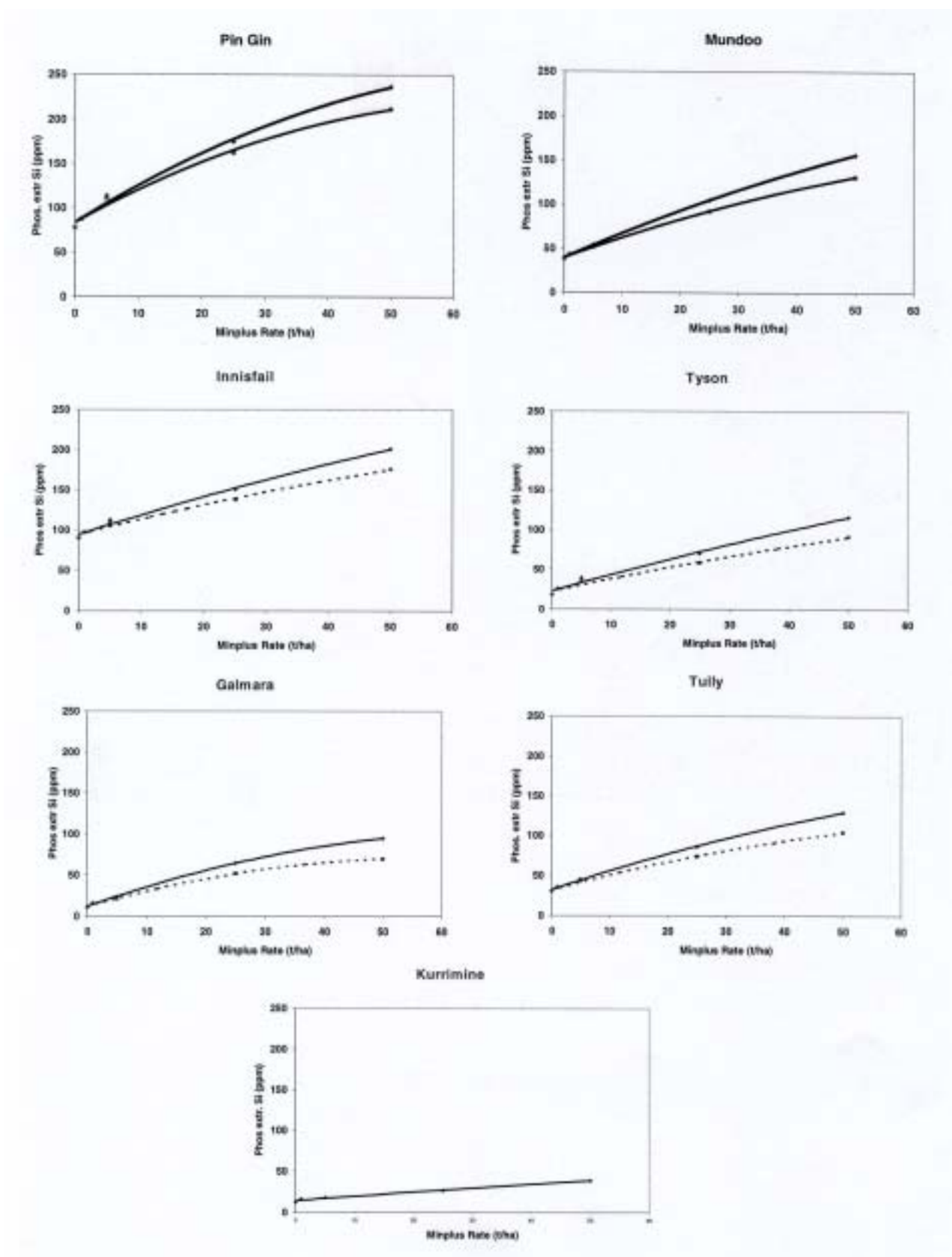


Figure 3.17 Amounts of silicon extracted (ppm) by a phosphate – acetate buffer with increasing application rates of Minplus™ in the seven studied soils from the humid tropical region of north Queensland.

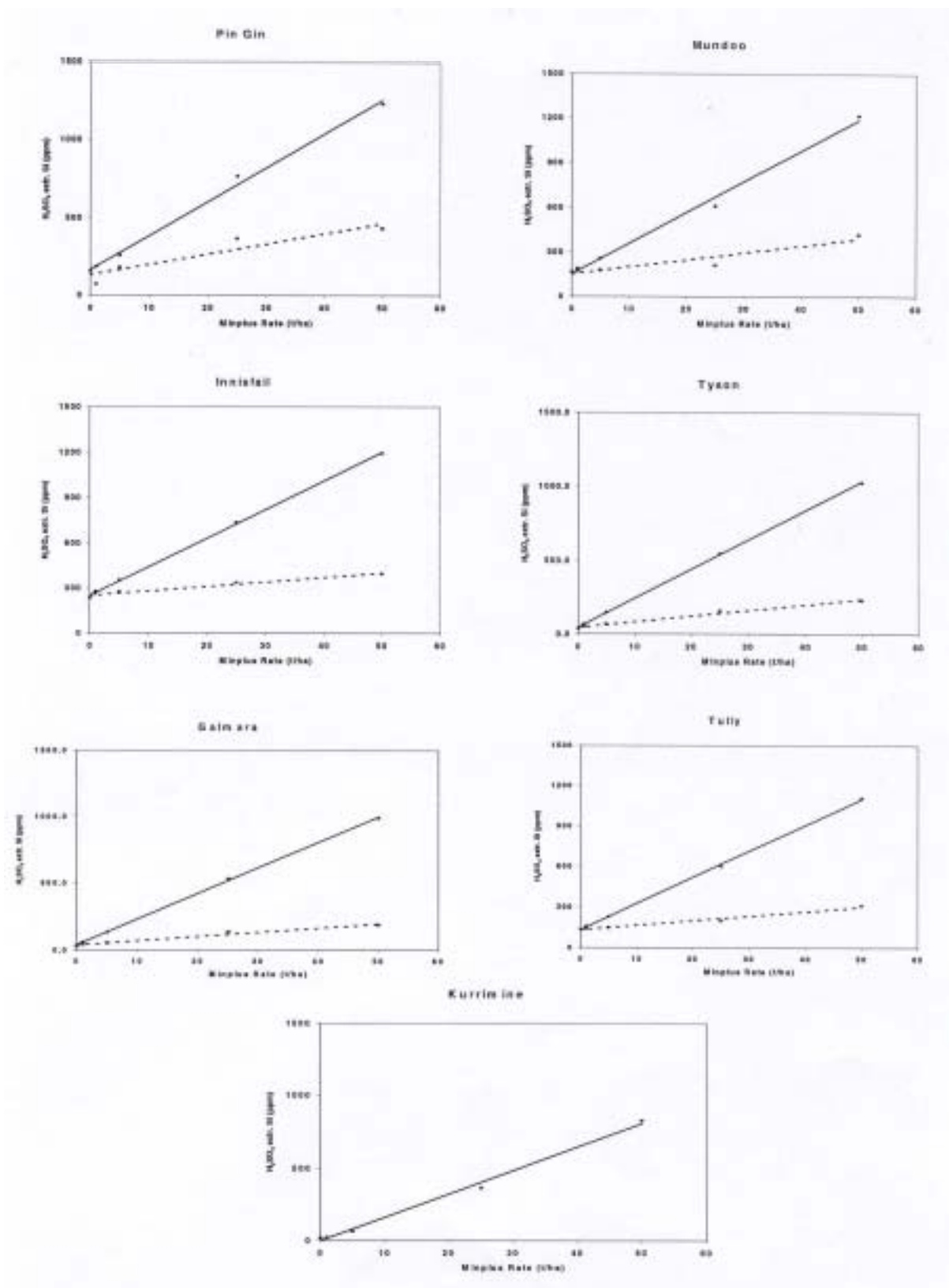


Figure 3.18 Amounts of silicon extracted (ppm) by 0.005 M  $H_2SO_4$  with increasing application rates of Minplus™ (0, 1, 5, 25, 50 t/ha) in the seven studied soils from the humid tropical region of north Queensland.

## Conclusions

Unfortunately, the estimation of Minplus<sup>TM</sup>-derived sorbed silicon by each of these methods is not consistent. Linear equations of sorbed silicon versus Minplus<sup>TM</sup> application rates were calculated for the amounts of silicon extracted by the phosphate–acetate buffer and weak sulphuric acid, and the results are summarised in Table 3.11. The slope constant of each equation shows the amount of sorbed silicon for each tonne of Minplus<sup>TM</sup> applied; it is seen that the constant for each soil associated with the H<sub>2</sub>SO<sub>4</sub> extractant is 2-3 times greater than that for the phosphate – acetate extractant.

The usefulness of the four extractants discussed above in predicting soil responses to silicon applications is yet to be conclusively demonstrated; it will require a combination of carefully constructed field trials and soil analytical determinations. Only after a better understanding has been gained of the forms of silicon in soils that are associated with plant uptake, and of the critical values that predict the likelihood of plant responses in different soils, will it be possible to assess whether soil silicon deficiency can be adequately addressed by the application of Minplus<sup>TM</sup> or any other silicate-based soil conditioners.

**Table 3.11. Linear equations relating the amount of silicon sorbed in the soil (ppm) that may be extracted by the phosphate–acetate buffer and weak sulphuric acid to Minplus<sup>TM</sup> application rate (t/ha). The slope constant (in bold font) is the amount of sorbed silicon in the soil supplied by each tonne of Minplus<sup>TM</sup>.**

Soil	Phosphate – Acetate Extractant	0.005 M H <sub>2</sub> SO <sub>4</sub> Extractant
<b>Pin Gin</b>	Silicon, ppm = <b>2.6</b> (Minplus <sup>TM</sup> , t/ha) + 88	Silicon, ppm = <b>6.7</b> (Minplus <sup>TM</sup> , t/ha) + 133
<b>Mundoo</b>	Silicon, ppm = <b>1.8</b> (Minplus <sup>TM</sup> , t/ha) + 41	Silicon, ppm = <b>4.8</b> (Minplus <sup>TM</sup> , t/ha) + 152
<b>Innisfail</b>	Silicon, ppm = <b>1.6</b> (Minplus <sup>TM</sup> , t/ha) + 96	Silicon, ppm = <b>3.0</b> (Minplus <sup>TM</sup> , t/ha) + 251
<b>Tyson</b>	Silicon, ppm = <b>1.4</b> (Minplus <sup>TM</sup> , t/ha) + 23	Silicon, ppm = <b>3.8</b> (Minplus <sup>TM</sup> , t/ha) + 45
<b>Galmara</b>	Silicon, ppm = <b>1.2</b> (Minplus <sup>TM</sup> , t/ha) + 15	Silicon, ppm = <b>3.2</b> (Minplus <sup>TM</sup> , t/ha) + 38
<b>Tully</b>	Silicon, ppm = <b>1.5</b> (Minplus <sup>TM</sup> , t/ha) + 34	Silicon, ppm = <b>3.4</b> (Minplus <sup>TM</sup> , t/ha) + 131

## 4. Plant responses in the field to Minplus™

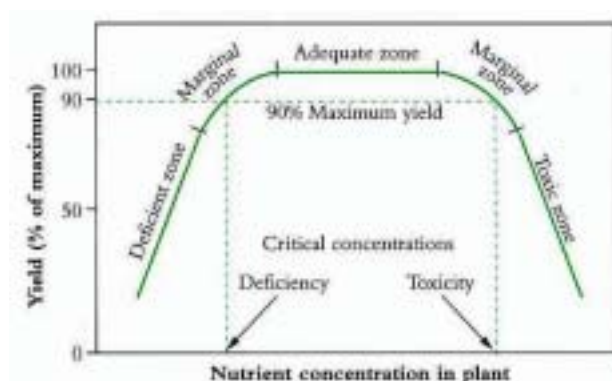
### 4.1 Research approach

#### 4.1.1 Plant nutrients and plant growth

Plants will grow well where light, water, and all the essential nutrients are available in the soil. One of the most fundamental of the modern discoveries in plant science, ‘*The Law of the Minimum*’ was proposed by Justus von Liebig in 1862. The law states that the level of plant production can be no greater than that allowed by the most limiting of the essential plant growth factors in the following words:

*“... every field contains a maximum of one or more and a minimum of one or more nutrients. With this minimum, be it in lime, potash, nitrogen, phosphoric acid, magnesia or any other nutrient, the yields stand in direct relation. It is the factor that governs and controls ... yields. Should this minimum be lime ... yield ... will remain the same and be no greater even though the amount of potash, silica, phosphoric acid, etc ... be increased a hundred fold.”* (Tisdale et al. 1993, p.8)

This means that a deficiency in one essential element in the soil will limit plant growth responses to all the other elements, even though they may be present in the soil in adequate amounts. If the element that is limiting plant growth is added to the system in an adequate amount, then growth will be inhibited by the next most limiting element. Supplying adequate amounts of successively limiting elements will allow the plant to achieve its full growth potential.



**Figure 4.1** Critical concentrations of plant nutrients for diagnosing nutrient deficiency and toxicity in plants. Source: Smith and Loneragan (1997, p. 11).

Critical concentrations, defined by the Law of the Minimum, set the nutrient levels needed for optimal (90 % of maximum) plant yields (Fig. 4.1). The availability of plant nutrients is limited in the ‘Deficient zone’ where plant growth increases with increasing nutrient concentration in the soil solution. Growth is limited by several factors: the absence of an essential element from the soil, the element being present in the soil but in a form that is unavailable to the plant (often the case when an element such as phosphorus is present in the soil in an almost insoluble mineral such as apatite, or when a metal such as iron is not available in a soluble, chelated form that can be taken up by the plant), or because of an imbalance among the amounts of the elements that are present. Nutrient deficiencies usually become evident in the typically stunted growth of affected plants, which have growth disorders evident in poor root development, foliar symptoms of deficiency, poor crop yields, and poor nutritional value in the produce.

In the ‘Adequate zone’ (Fig. 4.1), plants are supplied with sufficient nutrient to meet their growth requirements and provide a near-optimal yield of the order of 90% of the maximum possible yield; growth is not enhanced by supplying more nutrient than the plant requires. In the ‘Toxic zone’, plant growth is reduced, sometimes to the point of the death of the plant, because of an over-supply of the nutrient. Such a situation will occur in

extremely acidic soils where manganese or aluminium may attain toxic concentrations in the soil solution, even though the elements are present in only tiny amounts.

#### **4.1.2 Understanding plant growth responses to soil treatments**

It is evident from the research results reported in the preceding sections of this report, that applications of Minplus™ rock dust have the capacity to effect a number of significant changes to the mineralogical and chemical properties of highly weathered tropical soils. They include:

- increased negative charge in the soil,
- increased basic cation supply in the soil,
- improved cation exchange capacity of the soil, which enhances the capability of the soil to retain cations against leaching processes and to supply cations to plants,
- reduced soil acidity,
- a small contribution to plant-available phosphorus in the soil,
- marked reductions in phosphorus fixation capacity of particular soils.

The consequence of these changes in soil properties is improved plant growth in a suite of soils that are important to agricultural, horticultural, and silvicultural production in the humid tropics of Australia, and probably throughout the world.

Experimental trials using soils and plants grown in pots kept under controlled conditions in a shadehouse or glasshouse can be used to identify plant growth responses to any treatments that are imposed on the soil. Such experimental results should always be related to actual growing conditions in the field where there is less control over the prevailing environmental conditions, especially variations in the weather, soils, and the incidence of weeds and pests.

An attempt is made in this chapter to set out the results of a series of pot trials and field trials on several Minplus™-treated soils from north Queensland, using a range of bioassay indicator plants (e.g. tomatoes, silk sorghum, native grasses, exotic pasture species including grasses, and herbaceous and shrub legumes), as indicators of growth responses.

The research has used relative growth responses of the indicator plants to provide bioassessments of the efficacy of the soil rejuvenation induced by applications of Minplus™ rock dust. Three major research issues have been addressed in a suite of experiments performed by a number of researchers. They are:

- the extent to which calcium and magnesium deficiencies or imbalances have been overcome by Minplus™ applications to highly weathered tropical soils,
- the extent to which Minplus™ applications have raised soil pH and thereby reduced the negative influence of high levels of exchangeable aluminium, and have increased the availability of macronutrients in the soil,
- the influence of Minplus™ applications on the exchange complex of the soil such that the phosphate fixation capacity of the soil is reduced and phosphatic fertilisers are rendered more efficient.

#### **4.1.3 Materials and methods**

While Burkett (1998) provided an understanding of some of the effects of applications of Minplus™ to 7 highly weathered soils of the Innisfail – Tully area, other activities within the present project have focused on the details of other soils, including:

- the red basaltic Pin Gin Series Soil (Table 3.1) from site on a tea plantation located some 25 km west of Innisfail on the Palmerston Highway (de Silva in preparation), and from a banana farm located some 15 km west of Innisfail on the Palmerston Highway (Smallwood 1998; Satimbre 2001),

- the white quartzitic sands of the Cape Flattery Silica Mine, located on the Queensland coast some 120 km north of Cooktown (Horner 2000),
- the yellow Tully Series Soil formed in granitic alluvium near Tully (Brown 1998),
- the Heatley and Black Series Soils from the agricultural plots on the campus of James Cook University, Townsville (Satimbre 2001).

The bulk of the detailed experimental work on plant growth responses to Minplus™ applications has been performed, however, on the Innisfail Clay Series located on the campus of the Tropical North Queensland Institute of TAFE, Johnstone College, Innisfail (17.5°S, 146° E), where a field study site was established in 1998.

The major aim of the initial field trial at the TAFE College, Innisfail, was to establish the nature of growth responses of variety of pasture species on the Innisfail Clay to particular combinations of soil conditioners (Blend 3 dolomitic lime, Portland cement, and low and high application rates of Minplus™) with 4 different phosphatic fertiliser treatments. Progress towards answering the following research questions is reported in this Chapter:

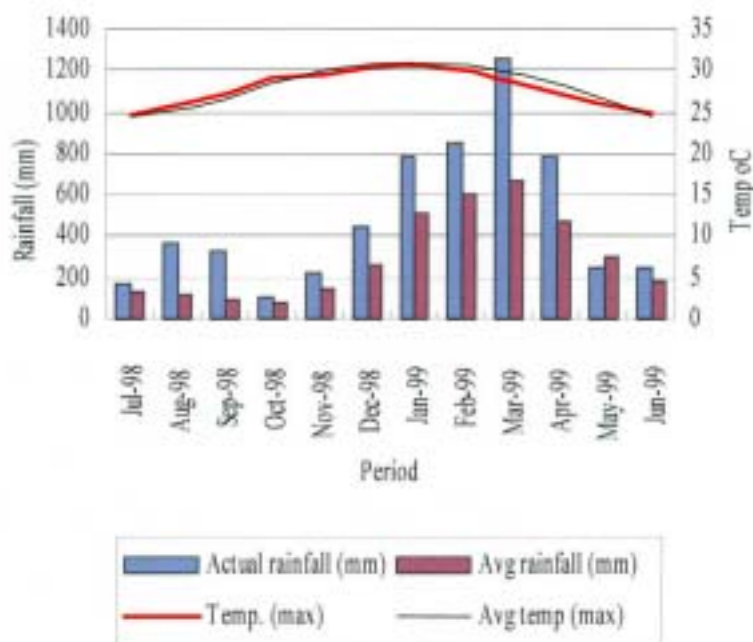
- How did the combinations of soil conditioners and phosphatic fertiliser treatments affect soil chemical properties?
- Did any particular combination of soil conditioner and phosphatic fertiliser minimise growth deficiencies attributable to phosphate fixation?
- Which soil conditioner – fertiliser treatment promoted the establishment of herbaceous legumes?
- Which soil conditioner – fertiliser treatment produced the greatest above-ground plant mass at maturity?
- Did any of the soil conditioner – fertiliser treatments favour the growth of any particular pasture plant species?

## **4.2 Field trial: the Innisfail Clay**

### **4.2.1 The experimental site and soil**

The study area lies on an almost flat alluvial terrace of the North Johnstone River and is above the height of any floods within living memory. The climate is humid tropical with a typically strongly seasonal and highly variable annual rainfall of 4,500 mm and an average of 159 raindays per year (Fig. 4.2).





**Figure 4.2** Actual monthly rainfall and actual daily maximum temperatures at Innisfail for July 1998 to June 1999 ([www.bom.gov.au](http://www.bom.gov.au)), and corresponding long-term climatic averages (Comm. Aust., Bur. Met. 1988).

Soils of the Innisfail Series were described by Murtha (1986) as brown or reddish brown, well drained, acidic (pH of topsoil 5.3 and 5.5 in the subsoil), light clays with uniform or gradational soil profiles ranging in texture from silty clay loam to medium clay. The soil is referred to in the present report as the Innisfail Clay and has formed in river alluvium derived primarily from basaltic sources, with some inputs from granitic and metamorphic rock terrains. Some selected soil properties from a number of literature sources are summarised in Table 4.1. The clay fraction of 43% is dominated by kaolinite and the soil has a high permanent negative charge and a relatively high CEC (Gillman and Abel 1987), suggesting that it is less likely to lose cations through leaching than most of the other soils of the Innisfail – Tully area. Nevertheless, the soil is not regarded as one of the prime soils in the region because of its low pH, low content of plant available phosphorus, low cation exchange capacity, and its soil nutrient levels become rapidly depleted under agriculture (Teitzel and Bruce 1972).

The experimental site of 2.1 ha (108 x 192 m) had been cleared of tropical rainforest more than 25 years ago and a *Brachiaria decumbens* (signal grass) pasture established. The stoloniferous grass was introduced to the region from Uganda in 1936 and its vigorous and aggressive growth in a wide range of well drained tropical soils inhibits the establishment of twining or erect herbaceous legumes (Loch 1977). The pasture included considerable amounts of *Mimosa pudica* (sensitive weed, which is a prickly herbaceous legume), with lesser amounts of the herbaceous legume *Desmodium heterophyllum* (hetero) and *Arachis pintoii* (forage peanut). Prior to establishment of the experimental plots, the paddock had been grazed intermittently by a small herd of cattle, slashed regularly, and weeds controlled by herbicide applications. No fertiliser had been applied since 1994, and perhaps a longer time previously.

Initially, in mid-1998, a set of 40 surface soil samples (cores 7.2 cm diameter x 10 cm deep) were collected on a 20 x 20 grid pattern over the site. A core sampler was used in that it allowed for the ready determination of soil bulk density (Rayment and Higginson 1992) from the same samples to be used in chemical analyses. Analyses of these samples provided 'baseline soil data' (Table 4.1) which indicated only extremely small variations in soil chemical properties over the whole of the site.

**Table 4.1** Mean values and standard deviations in parentheses, where available, of selected chemical properties of surface soil samples (0-10 cm layer) from various profiles of the Innisfail Clay from the Innisfail – Tully region.

Sources: Murtha (1986), Gillman and Abel (1987), Gillman and Bristow (1990), and baseline samples collected in 1998, just before the field experimental plots were established at the Johnstone College of TAFE, Innisfail (Burton 1999).

Data source:	Murtha (1986)	Gillman and Abel (1987)	Gillman and Bristow (1990)	Baseline data: Burton (1999)
No. of samples:	unknown	5	5	40
Site history:	some natural vegetation; most cultivated	cultivated	cultivated	pasture; no fertiliser since 1994 at latest
<b>Soil chemical properties:</b>				
<b>pH <sup>++</sup></b>	<b>5.3</b>	<b>4.7</b> (0.2)	<b>4.6</b>	<b>4.6</b> (0.06)
<b>Exch. Ca</b> cmol <sub>c</sub> / kg	<b>1.46</b>	<b>1.80</b> (2.00)	<b>3.3</b>	<b>2.21</b> (0.45)
<b>Exch. Mg</b> cmol <sub>c</sub> / kg	<b>1.40</b>	<b>0.90</b> (0.80)	<b>1.3</b>	<b>1.23</b> (0.16)
<b>Exch. K</b> cmol <sub>c</sub> / kg	<b>0.35</b>	<b>0.40</b> (0.17)	<b>0.8</b>	<b>0.38</b> (0.14)
<b>Exch. Na</b> cmol <sub>c</sub> / kg	<b>0.08</b>	<b>0.03</b> (0.01)	<b>0.1</b>	<b>0.09</b> (0.01)
<b>Total exch. basic cations</b> cmol <sub>c</sub> / kg	<b>3.29</b>	<b>3.13</b> (2.40)	<b>5.5</b>	<b>3.91</b> (0.59)
<b>Exch. (H + Al)</b> cmol <sub>c</sub> / kg	<b>3.0</b>	<b>2.6</b> (1.4)	<b>0.95</b>	<b>1.20</b> (0.35)
<b>Effective cation exch. capacity</b> <b>ECEC</b> * cmol <sub>c</sub> / kg	<b>6.29</b>	<b>5.73</b>	<b>6.45</b>	<b>5.11</b> (0.59)
<b>(H + Al) as % of ECEC</b>	<b>47.7</b>	<b>45.3</b>	<b>14.7</b>	<b>23.5</b>
<b>Plant available P</b> 0.005 M H <sub>2</sub> SO <sub>4</sub> ppm	<b>142</b>	<b>38</b> (30)	n.a.	<b>35</b> (14)

\* Effective cation exchange capacity (ECEC) = sum of exchangeable basic and acidic cations.

<sup>++</sup> pH determinations in water by (Murtha 1986), and in 0.002M CaCl<sub>2</sub> by Gillman and Abel (1987), Gillman and Bristow (1980), and Burton (1999)

## 4.2.2 Soil conditioners

A fully randomised 10 plot design, replicated in 4 blocks was established, after the pasture had been slashed (Fig. 4.3). Experimental plots 40 m long by 4 m wide were marked out in the pasture, with 2 m wide buffer strips of pasture left between plots. The following soil conditioners were applied to the plots on 19 October 1998:

- **Nil:** control,
- **Lime:** weakly dolomitic lime, “Blend 3”: calcium carbonate with 3% magnesium carbonate [ $\text{Ca}_{0.97}\text{Mg}_{0.03}\text{CO}_3$ ] applied at a rate of 2.5 t/ha.

This amendment was supplied by North Queensland Spreading Services, Innisfail, and is the most widely used liming agent in the area. The rate of application chosen offers the best compromise between what is needed by the soil and what is readily afforded. An application rate of 2.5 t/ha (1 t / acre) was chosen to allow comparisons of the efficacy of all the soil conditioners on a common application base.

- **Cement:** Portland cement applied at a rate of 2.5 t/ha .

Partington (1939) has shown cement to be a mixture of tricalcium silicate [ $3\text{CaO}, \text{SiO}_2$ ], tricalcium aluminate [ $3\text{CaO}, \text{Al}_2\text{O}_3$ ], calcium orthosilicate [ $2\text{CaO}, \text{SiO}_2$ ], pentacalcium trialuminate [ $5\text{CaO}, 3\text{Al}_2\text{O}_3$ ], free lime [ $\text{CaO}$ ], and not less than 3% ferric oxide [ $\text{Fe}_2\text{O}_3$ ]. Cement is a readily available, though expensive, bulk source of finely ground calcium silicates. It was anticipated that the cement would act as an effective liming agent and also provide some of the benefits of silicate additions to the soil as described by Leonardos *et al.* (1987).

- **Low Minplus<sup>TM</sup>:** Minplus<sup>TM</sup> (calcium and magnesium silicates) applied at a rate of 2.5 t/ha.

Anecdotal evidence from Minplus<sup>TM</sup> applications in the region suggests that Minplus<sup>TM</sup> acts as an effective liming agent to raise the pH of the soil when applied at a rate of 2.5 t/ha, although better results have been obtained from higher application rates, or from repeated applications in successive years (Campe 1993; Edwards 1993). Other anticipated benefits from Minplus<sup>TM</sup> applications were improved calcium, magnesium, and phosphorus nutrition of plants, improved cation exchange capacity of the soil, and reduced phosphate fixation in the soil.

- **High Minplus<sup>TM</sup>:** Minplus<sup>TM</sup> applied at the high rate of 25 t/ha.

The high rate of application was chosen in order speed up any reactions that might occur over time by dramatically increasing the mass of elements supplied to the soil.

A spreading truck was used to apply the high rates of Minplus<sup>TM</sup> (Fig. 4.4); all the other amendments were applied by hand. In order to accommodate the boom of the spreading truck, the plots receiving the high rates of Minplus<sup>TM</sup> were made 7.2 m wide and adjacent 2 m wide buffer strips were maintained, as in the narrower plots.

All the amendments were worked into the uppermost part of the soil below the pasture with a 3-tyne chisel plough.

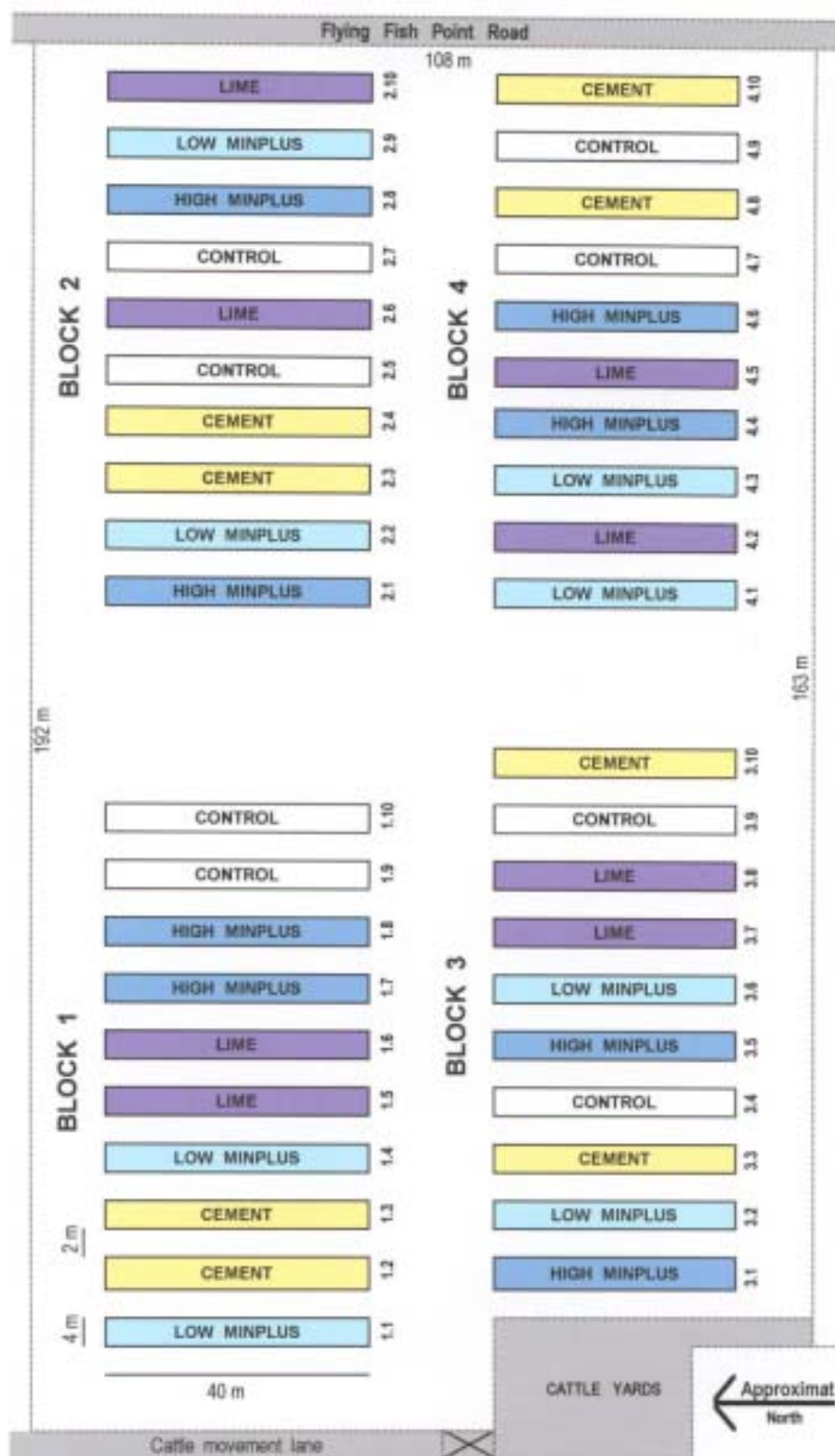


Figure 4.3 Schematic diagram of the randomised experimental plots at the Johnstone College, Tropical North Queensland Institute of TAFE, Innisfail. Plots were 40 m long by 4 m wide (7.2 m wide for the 'High Minplus<sup>TM</sup>' treatments), with 2 m buffer zones between plots within blocks. A buffer zone of at least 6 m was left beside all the boundary fences. Plot numbers within Blocks 1 – 4 are indicated.



**Figure 4.4** Spreading Minplus™ at a rate of 25 t/ha over one of the ‘High Minplus™’ plots of the field trial at the Johnstone College of TAFE, Innisfail. (Photograph by F. Jacintho).

### 4.2.3 Fertilisers

The plots and their dense pasture stands were rotary hoed on 14 December 1998 (having received some 700 mm of rain since the amendments were spread, Fig. 4.2) and split so as to be only 20 m long by 4 m or 7.2 m wide. Four phosphatic fertiliser treatments were applied to the cultivated soil at random across the 20 sub-plots within each of the 4 blocks (Fig. 4.5):

- **Nil:** (control),
- **Superphosphate:** (single superphosphate which is processed rock phosphate containing calcium, phosphorus and sulphur [ $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O} + \text{CaSO}_4$ ] at a rate of 246 kg / ha. This widely used fertiliser was applied at the ‘normal’ rate for pasture responses throughout the region. The rate of 246 kg / ha was adopted for each of the fertilisers used in the experiment.
- **Diammonium phosphate:** (“DAP”:  $(\text{NH}_4)_2\text{HPO}_4$ ) at a rate of 246 kg/ha. DAP is a more soluble phosphatic fertiliser than superphosphate (Handreck and Black 1994), hence may also produce plant responses more rapidly than superphosphate.
- **Rock phosphate:** (“Q Phos”: mainly fluorapatite [ $\text{Ca}_5(\text{PO}_4)_3\text{F}$ ] and hydroxyapatite [ $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ ] ) at a rate of 246 kg / ha. Q Phos is a phosphatic fertiliser that is less soluble and slower-acting than superphosphate (Handreck and Black 1994).

The superphosphate and rock phosphate treatments also received a supplementary urea dressing (0.767 kg over the 4 m wide plots and 1.385 kg over the 7.2 m wide plots) to match the nitrogen applied in the diammonium phosphate treatment. The control plots for the fertiliser treatments received no supplementary nitrogen dressing.

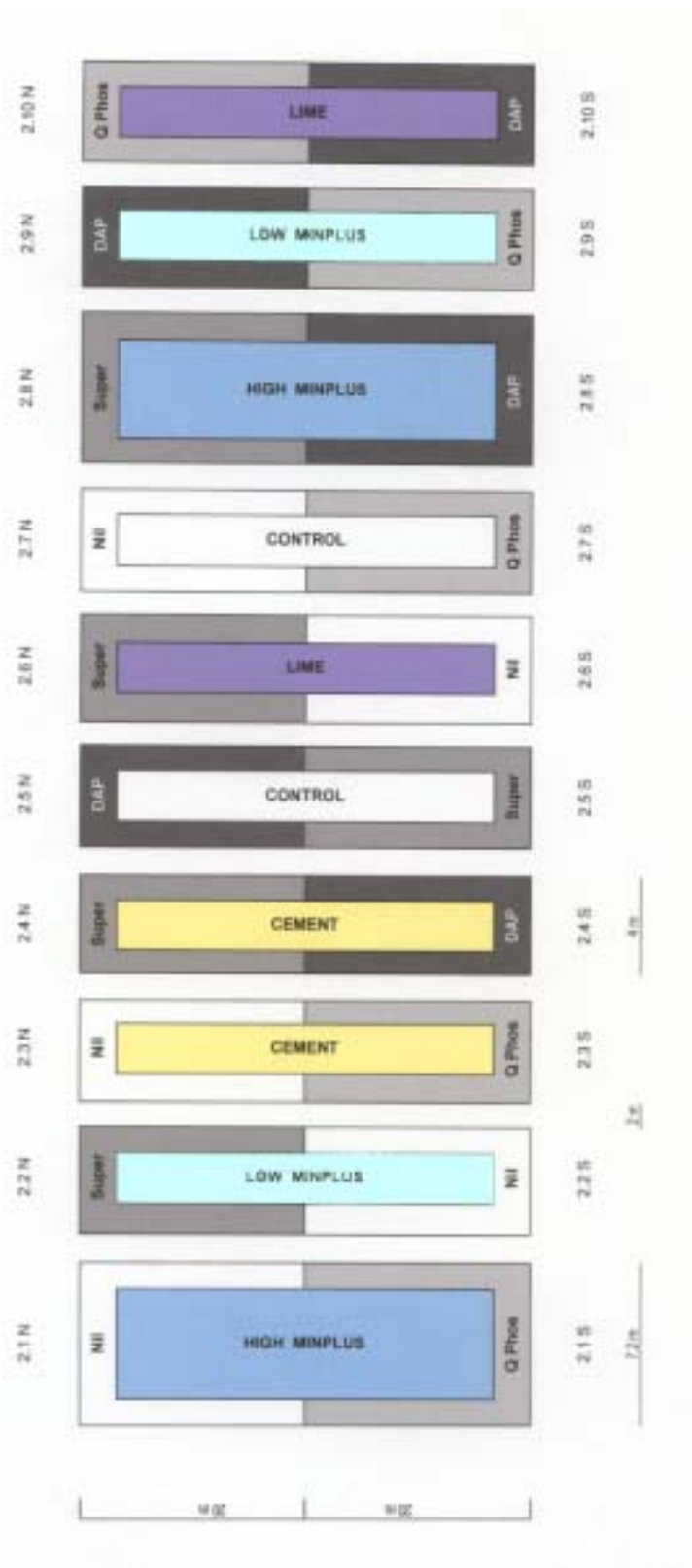


Figure 4.5 Schematic representation of the randomised soil conditioner – phosphatic fertiliser treatment patterns in one of the experimental blocks (Block 4) of the field trial at the Johnstone College of TAFE, Innisfail. The plots delineating the individual combinations of soil conditioner and fertiliser application were 20 m long and 4m wide (7.2 m wide for the High Minplus™ plots). Despite their delineation on this schematic, the treatment combinations were applied in the field to the 20 m length and full width of each sub-plot.

#### 4.2.4 Sown legumes

At the same time as the fertilisers were applied, inoculated seeds of the 5 legume species listed in Table 4.2 were broadcast by hand uniformly across all the plots at a rate of 1 kg / ha (10 kg / ha for *Arachis pinto*). Stem cuttings of *A. pinto* were cut by tractor-mounted slasher in an adjacent paddock and were spread by hand thickly over the plots. The seed and cuttings were incorporated into the soil by light cultivation by a 3-tynd plough to a depth of 2 cm.

**Table 4.2** Legumes sown into the *Brachiaria decumbens* pasture at the Johnstone College of TAFE, Innisfail.

Legume species	Cultivar	Common name	Inoculum used
<i>Aeschynomene americana</i>	Glen Joint Vetch	Glen joint vetch	CB 2312
<i>Arachis pinto</i>	Amarillo	Pinto, or forage peanut	none
<i>Centrosema pubescens</i>	Cardillo	Cardillo centro	none
<i>Desmanthus virgatus</i>	Jabiru	Jabiru desmanthus	CB 3126
<i>Stylosanthes guianensis</i>	Cook	Cook stylo	CB 1650

The legumes are all suitable for pasture improvement in the humid tropics (Partridge 1998). The phosphorus supply in the soil is the factor most limiting herbaceous legume growth in the tropical pastures of Australia (Russell 1978) and elsewhere (Kanehiro 1983).

Glen joint vetch is suited to low fertility soils of the humid tropics, growing best from seed with a low ground cover as dense grass covers inhibit its establishment; aggressive growth in the wet season will overcome less vigorous grasses (Partridge 1998). Pinto peanut is well adapted to the Innisfail Clay and has established very well at other locations adjacent to the experimental site. Both Cook stylo and Cardillo centro are known to respond well to superphosphate applications and have formed good pastures with *B. decumbens* (Andrew and Jones 1978; Robinson 1983). The desmanthus was thought to be the least likely of the introduced legumes to thrive in the acidic soil conditions of the humid tropics because it grows preferentially under much drier conditions in clay soils with neutral to alkaline pH (Partridge 1998). It is an annual and will grow well with tall grasses, but usually needs a few seasons to build up adequate seed reserves in the soil (Partridge 1998; Salinas and Gauldron 1989).

#### 4.2.5 Monitoring and managing changes in pasture growth and soil properties

Samples of the above ground standing crop of the pasture swards were collected on 14 – 15 March 1999, 3 months after planting, to provide estimates of the responses of the pasture species to “establishment” conditions. The samples were cut at the ground surface in one 0.5 x 0.5 m quadrat within each of the soil conditioner – fertiliser treatments, with the measurements replicated in each of the 4 experimental blocks. There had been 2,600 mm of rain during the growing period (Fig. 4.2).

A similar suite of pasture samples was collected on 1-2 July 1999, after most of the legumes had flowered and set seed, some 6 months and a total of 3900 mm of rainfall since planting. These samples indicate the plant masses that may be achieved at “maturity”. Plant samples were collected from 3 replicates of 0.5 x 0.5 m quadrats in each of the 80 soil conditioner – fertiliser treatments. At the same time, soil cores (7.2 cm diameter x 10 cm deep) were collected from each of the 240 plant sample quadrats. A third set of soil samples was collected in triplicate in July 2000 from each of the treatments in Blocks 1 and 2 (Fig 4.3).

All the plant materials from both harvests were sorted into species, dried at 60 °C, and weighed in order to determine relative growth differences among the species.

Crotalaria bushes and other tall weeds were removed by hand from the plots in October 1999 and all the plots were slashed in December 1999, in February 2000, and in September 2000. Blocks 3 and 4 were slashed in December 2000. The experimental paddock was opened to cattle grazing in August – December 2000.

The soil conditioners were re-applied at the original application rates on 27 October 2000, in preparation for planting Plots 1.2, 1.4, 1.6, 1.8, 1.10 of Block 1 (Fig. 4.3) to bananas (M. Burton, in preparation), and to all the sub-plots of Block 2 planted to shrub legumes on 13 December 2000 (M. Pomares, in preparation). Phosphatic fertilisers were re-applied in the December 2000 plantings.

### 4.3 Soil changes induced by treatments

In attempting to interpret the results presented below, it is important to realise that the different soil conditioners and fertilisers have different chemical compositions and produce different contents of calcium, magnesium, phosphorus, and silicon in the treated soils. These differences are shown in Table 4.3.

**Table 4.3** Amounts (t/ha) of calcium, magnesium, phosphorus, and silicon added to the Innisfail Clay in the amendment- fertiliser treatments applied to the 80 experimental sub-plots of the field experiment at Johnstone College of TAFE, Innisfail.

	Element	Total amount of element added (t/ha)			
		Control	Q Phos	Super	DAP
<b>Control</b>	<b>Ca</b>	0	0.08	0.05	0
	<b>Mg</b>	0	0	0	0
	<b>P</b>	0	0.04	0.02	0.06
	<b>Si</b>	0	0	0	0
<b>Lime</b>	<b>Ca</b>	0.54	0.62	0.60	0.54
	<b>Mg</b>	0.33	0.33	0.33	0.33
	<b>Si</b>	0	0	0	0
	<b>P</b>	0.00	0.04	0.02	0.10
<b>Cement</b>	<b>Ca</b>	0.75	0.85	0.80	0.75
	<b>P</b>	0.00	0.04	0.02	0.06
	<b>Mg</b>	0	0	0	0
	<b>Si</b>	0.53	0.53	0.53	0.53
<b>Low MP</b>	<b>Ca</b>	0.16	0.24	0.21	0.16
	<b>Mg</b>	0.17	0.17	0.17	0.17
	<b>P</b>	0.01	0.05	0.03	0.07
	<b>Si</b>	0.50	0.50	0.50	0.50
<b>High MP</b>	<b>Ca</b>	1.58	1.66	1.63	1.58
	<b>Mg</b>	1.65	1.65	1.65	1.65
	<b>P</b>	0.08	0.12	0.1	0.14
	<b>Si</b>	5.00	5.00	5.00	5.00

Not all the soil chemical analyses that were intended to be performed on the 3 sets of samples have been completed at this time. The data that are available are summarised in Tables 4.4 – 4.12.

The numbers in the tables represent the analyses of a suite of 3 soil sample replicates collected from each of the 80 treatment sub-plots after exposure to one wet season. In order to reduce the number of samples to be analysed to a manageable number for the 9 laboratory determinations made, each of the field samples was sub-sampled and the subsamples bulked to provide one sample per soil conditioner-fertiliser sub-plot within each experimental block. Hence, the values in each cell of Tables 4.4 – 4.12 represents mean values calculated from analyses of 4 bulked soil sub-samples, one sub-sample derived from each experimental block.

#### 4.3.1 Cation exchange properties

The results of analyses of the cation exchange properties of soil samples collected from the soil conditioner - fertiliser treatments are shown in Tables 4.4 – 4.8.



**Table 4.4** Mean exchangeable calcium contents (cmol/kg), and standard deviations shown in parentheses, of surface soils of each soil conditioner – fertiliser treatment of the field trial at Johnstone College of TAFE, Innisfail. Compulsive exchange (0.1M BaCl<sub>2</sub>/NH<sub>4</sub>Cl) extraction; mean values are derived from 4 replicates for each treatment. Source: Burton (1999).

	Exchangeable calcium (cmol <sub>c</sub> / kg)			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>2.6</b> (0.2)	<b>2.6</b> (0.5)	<b>2.6</b> (0.4)	<b>2.4</b> (0.4)
Lime	<b>4.3</b> (0.5)	<b>4.6</b> (0.7)	<b>4.9</b> (0.9)	<b>5.2</b> (0.3)
Cement	<b>5.2</b> (1.0)	<b>4.4</b> (0.4)	<b>4.8</b> (0.9)	<b>4.9</b> (1.1)
Low Minplus <sup>TM</sup>	<b>2.8</b> (0.4)	<b>2.4</b> (0.4)	<b>2.5</b> (0.4)	<b>2.6</b> (0.7)
High Minplus <sup>TM</sup>	<b>2.8</b> (0.7)	<b>3.0</b> (0.7)	<b>3.1</b> (0.3)	<b>3.0</b> (0.4)

**Table 4.5** Mean exchangeable magnesium contents (cmol/kg), and standard deviations shown in parentheses, of surface soils of each soil conditioner – fertiliser treatment of the field trial at Johnstone College of TAFE, Innisfail. Compulsive exchange (0.1M BaCl<sub>2</sub>/NH<sub>4</sub>Cl) extraction; mean values are derived from 4 replicates for each treatment. Source: Burton (1999).

	Exchangeable magnesium (cmol <sub>c</sub> / kg)			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>1.6</b> (0.2)	<b>1.6</b> (0.2)	<b>1.4</b> (0.1)	<b>1.3</b> (0.1)
Lime	<b>1.7</b> (0.3)	<b>1.9</b> (0.2)	<b>1.9</b> (0.3)	<b>1.8</b> (0.2)
Cement	<b>1.3</b> (0.2)	<b>1.4</b> (0.3)	<b>1.3</b> (0.1)	<b>1.3</b> (0.1)
Low Minplus <sup>TM</sup>	<b>1.6</b> (0.3)	<b>1.7</b> (0.3)	<b>1.8</b> (0.4)	<b>1.9</b> (0.7)
High Minplus <sup>TM</sup>	<b>2.8</b> (0.4)	<b>2.9</b> (0.7)	<b>2.9</b> (0.5)	<b>3.2</b> (0.6)

**Table 4.6** Mean exchangeable potassium contents (cmol/kg), and standard deviations shown in parentheses, of surface soils of each soil conditioner – fertiliser treatment of the field trial at Johnstone College of TAFE, Innisfail. Compulsive exchange (0.1M BaCl<sub>2</sub>/NH<sub>4</sub>Cl) extraction; mean values are derived from 4 replicates for each treatment. Source: Burton (1999).

	Exchangeable potassium (cmol <sub>c</sub> / kg)			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>0.3</b> (0.1)	<b>0.3</b> (0.1)	<b>0.3</b> (0.1)	<b>0.3</b> (0.1)
Lime	<b>0.4</b> (0.1)	<b>0.5</b> (0.1)	<b>0.3</b> (0.0)	<b>0.4</b> (0.2)
Cement	<b>0.3</b> (0.1)	<b>0.4</b> (0.1)	<b>0.3</b> (0.2)	<b>0.3</b> (0.1)
Low Minplus <sup>TM</sup>	<b>0.3</b> (0.2)	<b>0.3</b> (0.2)	<b>0.4</b> (0.3)	<b>0.3</b> (0.1)
High Minplus <sup>TM</sup>	<b>0.3</b> (0.0)	<b>0.3</b> (0.0)	<b>0.3</b> (0.0)	<b>0.6</b> (0.1)

**Table 4.7** Mean exchangeable sodium contents (cmol/kg), and standard deviations shown in parentheses, of surface soils of each soil conditioner – fertiliser treatment of the field trial at Johnstone College of TAFE, Innisfail. Compulsive exchange (0.1M BaCl<sub>2</sub>/NH<sub>4</sub>Cl) extraction; mean values are derived from 4 replicates for each treatment. Source: Burton (1999).

	Exchangeable sodium (cmol <sub>c</sub> / kg)			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)
Lime	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)
Cement	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)
Low Minplus <sup>TM</sup>	<b>0.1</b> (0.0)	<b>0.1</b> (0.0)	<b>0.1</b> (0.1)	<b>0.1</b> (0.0)
High Minplus <sup>TM</sup>	<b>0.2</b> (0.0)	<b>0.1</b> (0.0)	<b>0.2</b> (0.0)	<b>0.2</b> (0.0)

**Table 4.8 Mean effective cation exchange capacity (ECEC, cmol/kg), and standard deviations shown in parentheses, of surface soils of each soil conditioner – fertiliser treatment of the field trial at Johnstone College of TAFE, Innisfail. Compulsive exchange (0.1M BaCl<sub>2</sub>/NH<sub>4</sub>Cl) extraction; mean values are derived from 4 replicates for each treatment. Source: Burton (1999).**

	Effective cation exchange capacity (ECEC) (cmol <sub>c</sub> / kg)			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>5.7</b> (1.1)	<b>5.8</b> (0.2)	<b>5.5</b> (0.4)	<b>5.5</b> (0.3)
Lime	<b>6.9</b> (0.7)	<b>7.3</b> (0.4)	<b>7.5</b> (1.0)	<b>7.6</b> (0.3)
Cement	<b>7.4</b> (1.0)	<b>6.7</b> (0.1)	<b>6.8</b> (1.0)	<b>7.0</b> (0.9)
Low Minplus <sup>TM</sup>	<b>5.9</b> (0.8)	<b>5.6</b> (0.5)	<b>5.9</b> (0.9)	<b>6.0</b> (1.1)
High Minplus <sup>TM</sup>	<b>6.7</b> (0.5)	<b>6.8</b> (0.6)	<b>6.9</b> (0.6)	<b>7.2</b> (0.7)

There are no statistically significant differences across any row of Tables 4.3 – 4.8, which means that none of the fertilisers produced any significant effects on the exchange properties of the surface layer of the Innisfail Clay. This is a difficult result to explain, given the different solubilities of the fertilisers that were expected to influence the availability of exchangeable calcium and acidic cations in the soils.

With a few exceptions, there is a similar absence of significant differences down the columns of the tables, suggesting that, after one wet season, none of the soil conditioners has had a stronger effect than any other on the exchange properties of the soil. The exceptions include:

- *Exchangeable calcium inputs from the lime and cement treatments*

This result may be explained in terms of the relatively large amounts of calcium in the soil conditioners themselves (Table 4.3). Even though there was about 3 times as much calcium applied in the High Minplus<sup>TM</sup> treatment, the solubility of the rock dust is much lower than that of lime or cement. Hence, both the Low and High Minplus<sup>TM</sup> treatments, after one wet season, have exchangeable calcium contents no different from those of the untreated soil (Table 4.3). It will be interesting to see, with the passage of time and prolonged leaching under the high rainfall of the Innisfail area, if the exchangeable calcium values of the Minplus<sup>TM</sup> treatments increase as rapidly as the corresponding values decrease in the lime and cement treatments.

- *Exchangeable magnesium from the Minplus<sup>TM</sup> high application rate*

The High Minplus<sup>TM</sup> amendment contained much more magnesium than any of the other soil conditioners and no magnesium was supplied from any of the fertilisers. Therefore, the high exchangeable magnesium values in the soils which received a high application rate of Minplus<sup>TM</sup> may be traced directly to the chemistry of the soil conditioner and its application rate.

## 4.3.2 Soil acidity

### *Proportion of acidic cations constituting the effective cation exchange capacity*

All the soil conditioners, except for the Low Minplus<sup>TM</sup> dressings, made a significant reduction in the amounts of acidic cations to the exchange complex of the soil. The data show some variability, but no effect of the different fertilisers (Table 4.9). Nevertheless, the trends shown in Table 4.10 suggest that the order of efficiency of the soil conditioners at reducing the content of acidic cations was:

Cement > Lime > High Minplus<sup>TM</sup> > Low Minplus<sup>TM</sup>

**Table 4.9** Mean exchangeable acidic cations contents ( $H^+ + Al^{3+}$ ; cmol/kg), and standard deviations shown in parentheses, of surface soils of each soil conditioner – fertiliser treatment of the field trial at Johnstone College of TAFE, Innisfail. Salt extractable (1.0 M KCl) extraction; mean values are derived from 4 replicates for each treatment. Source: Burton (1999).

	Exchangeable acidic cations (cmol <sub>c</sub> / kg)			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>1.1</b> (0.3)	<b>1.2</b> (0.3)	<b>1.2</b> (0.3)	<b>1.5</b> (0.4)
Lime	<b>0.6</b> (0.1)	<b>0.5</b> (0.2)	<b>0.5</b> (0.2)	<b>0.4</b> (0.2)
Cement	<b>0.4</b> (0.1)	<b>0.5</b> (0.1)	<b>0.3</b> (0.2)	<b>0.4</b> (0.3)
Low Minplus <sup>TM</sup>	<b>1.1</b> (0.2)	<b>1.1</b> (0.5)	<b>1.1</b> (0.4)	<b>1.1</b> (0.5)
High Minplus <sup>TM</sup>	<b>0.8</b> (0.2)	<b>0.7</b> (0.5)	<b>0.7</b> (0.4)	<b>0.7</b> (0.3)

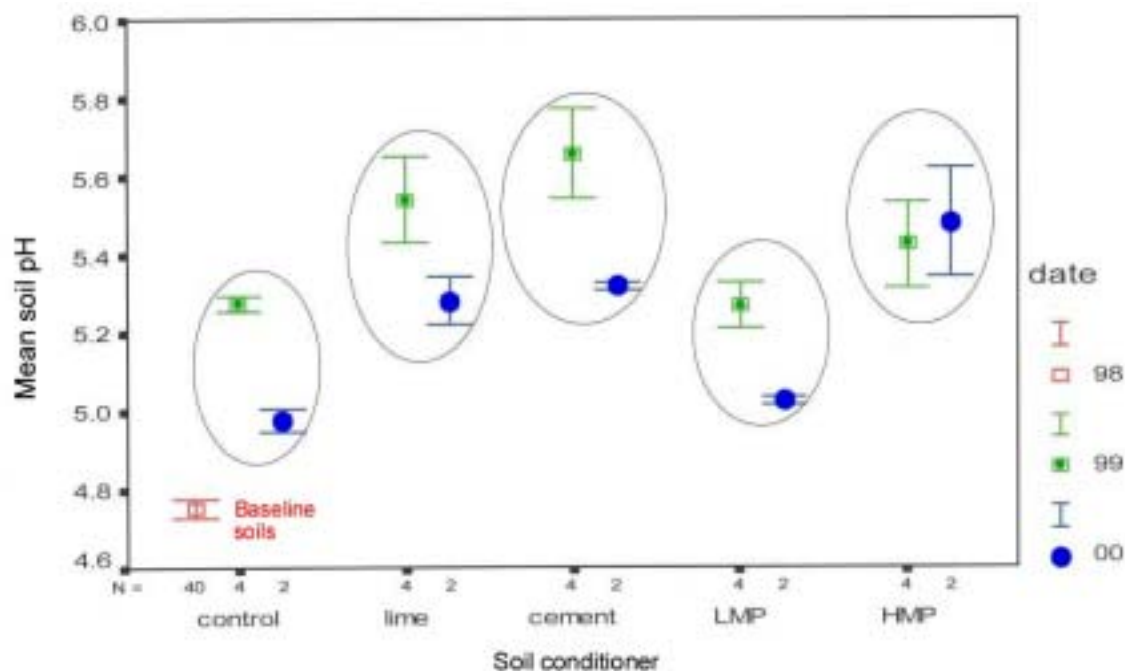
**Table 4.10** Mean exchangeable acidic cations ( $H^+ + Al^{3+}$ ) as percentages of the ECEC (cmol/kg) of surface soils of each soil conditioner – fertiliser treatment of the field trial at Johnstone College of TAFE, Innisfail. Mean values are derived from 4 replicates for each treatment. Source: Burton (1999).

	Exchangeable acidic cations as % of ECEC			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>18.9</b>	<b>21.2</b>	<b>21.4</b>	<b>26.8</b>
Lime	<b>8.0</b>	<b>7.4</b>	<b>6.6</b>	<b>5.2</b>
Cement	<b>5.4</b>	<b>6.7</b>	<b>5.1</b>	<b>5.6</b>
Low Minplus <sup>TM</sup>	<b>18.4</b>	<b>19.3</b>	<b>18.5</b>	<b>18.6</b>
High Minplus <sup>TM</sup>	<b>12.6</b>	<b>11.5</b>	<b>10.9</b>	<b>9.2</b>

#### *Changes in field pH of the treated soils*

Soils of the field plots that had been treated with the 5 soil conditioners (nil, lime, cement, low rate of Minplus<sup>TM</sup>, high rate of Minplus<sup>TM</sup>), but had no fertiliser applied, were sampled in July 1999, and again in July 2000. These sampling dates were after the soils had experienced one year's growth, and two year's growth, of the vigorous *Brachiaria*-legume pasture.

There was a significant increase of almost 0.5 soil pH units after establishment of the pasture (compare pH values for 'control' samples related to the '1998 Baseline Soil' data with the 'control' samples for 1999; Fig. 4.6). This relates to the effects of cultivation which opened up the soil, encouraged decomposition of the thick plant litter layer that had been incorporated into the soil, promoted limited water entry into the soil during the wet season, and sustained the establishment of the new grass-sown legume pasture. The soil pH showed a significant decrease of about 0.3 of a soil pH unit in the following growing season (compare data for the 'control' samples from 1999 and 2000; Fig 4.6).



**Figure 4.6** Changes after 2 wet seasons in the pH of topsoils (mean pH  $\pm$  2 standard errors for the 0-10 cm soil layer) of the Innisfail Clay that have been treated with different soil conditioners in the field trial at the Johnstone College of TAFE, Innisfail. Soil conditioners are: nil (control), Blend 3 dolomitic lime, Portland cement, and low rate of Minplus<sup>TM</sup> (LMP) all at 2.5 t/ha, and a high rate of Minplus<sup>TM</sup> (HMP) at 25 t/ha. Soil samples were collected in September 1998, July 1999, and July 2000.

The application of lime, cement, and the high rate of Minplus<sup>TM</sup> all produced a significant increases in soil pH compared with the controls (Fig. 4.6). This means that all 3 soil conditioners significantly reduced the acidity of the soil; the low rate of Minplus<sup>TM</sup> did not show any such trend (Fig. 4.6).

The reduction in soil acidity was sustained into the second year by any of the lime, cement, or low rate of Minplus<sup>TM</sup> treatment; the paired data for each treatment (in the ellipses of Fig. 4.6) show that the soil pH was lower by up to 0.3 soil pH units in the samples collected after the second wet season.

In contrast, however, the high rate of Minplus<sup>TM</sup> treatment produced an increase in soil pH (i.e. a reduction in soil acidity) that was not significantly different from that attained by the lime treatment (Fig. 4.6). More importantly, this increase in soil pH was sustained for 2 years with no increase in soil acidity through the second wet season (Fig. 4.6). This result is consistent with the reduction in acidic cations noted in the preceding Section.

Minplus<sup>TM</sup> has the capacity to reduce the acidity of the soil, and can also reduce the phosphate fixing capacity of acidic, highly weathered soils (see Section 3.4, above). It is clear that Minplus<sup>TM</sup> applications provide useful soil neutralising effects, which may be sustained for a longer duration in the soil than that provided by lime or cement. A laboratory leaching experiment was carried out in order to gain some information on just how long the soil conditioning effects of Minplus<sup>TM</sup> may persist in the soil. It is discussed in Chapter 8.

To determine just how much Minplus<sup>TM</sup> is needed to match the soil acidity neutralising effect of a particular lime application on a specific soil, with the effects sustained for an explicit time interval, are research issues that lie beyond the scope of the present project.

### 4.3.3 Phosphorus

The 'plant available phosphorus', or, 'BSES phosphorus' contents reported in all the results presented in the present report have been analysed using a weak acid extractant (0.005 M H<sub>2</sub>SO<sub>4</sub>), a 1:200 soil : extractant ratio, and extraction over 16 hours following the method of Kerr and von Steiglitz (1938). This method has been widely used throughout the north Australian tropics. Bruce and Bruce (1972) have suggested that, if the values for plant available phosphorus determined in this manner fall below 20 g / g, or below 20 ppm, then sugarcane growing on the soil will respond to phosphatic fertiliser applications. The higher threshold value of Toreu *et al.* (1988) of 40 g / g relates to the determination of plant available phosphorus by the BSES method and the resulting phosphorus value expressed as P<sub>2</sub>O<sub>5</sub> (G.P. Gillman, pers. comm.).

Table 4.11 shows the generally low plant available phosphorus contents of the topsoil samples collected in July 1999 from the various soil conditioner – fertiliser treatments some 6 - 9 months after application of the treatments, after one growing season. The large standard deviations indicate the high variability in the results. Nevertheless, all the analyses that produced outliers in the data set were repeated, with a similar outcome.

The high rate of Minplus<sup>TM</sup>, with any of the fertilisers, produced the highest plant available phosphorus contents in the soil (Table 4.11). The combination of phosphatic fertilisers with any of the other soil conditioners barely raised the plant available phosphorus contents of the soil above the level of the nil amendment – nil fertiliser control (Table 4.11). This suggests that at the relatively low rates of phosphatic fertiliser application employed, much of the added phosphorus was locked up in the soil and was not readily available for plant growth.

Statistically significant differences in the levels of plant available phosphorus occur between the soil conditioners and fertilisers, but there were no significant interactions between the soil conditioners and fertilisers (Burton 1999), indicating that the soil conditioners and fertilisers were acting independently of each other to achieve the difference.

**Table 4.11 Mean plant available phosphorus contents (mg /kg, or, ppm), and standard deviations shown in parentheses, of surface soils of each soil conditioner – fertiliser treatment from the field trial at Johnstone College of TAFE, Innisfail. Weak acid (0.005 M H<sub>2</sub>SO<sub>4</sub>) extraction; mean values are derived from 4 replicates for each treatment. Source: Burton (1999).**

	Plant available phosphorus ( g / g)			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>39.7</b> (6.6)	<b>42.4</b> (7.1)	<b>39.1</b> (10.3)	<b>37.6</b> (7.8)
Lime	<b>36.0</b> (8.5)	<b>42.4</b> (6.3)	<b>58.3</b> (35.2)	<b>47.6</b> (4.8)
Cement	<b>35.2</b> (8.3)	<b>37.8</b> (7.3)	<b>35.8</b> (7.0)	<b>48.1</b> (9.6)
Low Minplus <sup>TM</sup>	<b>33.9</b> (5.3)	<b>47.0</b> (6.9)	<b>38.2</b> (5.4)	<b>49.7</b> (12.0)
High Minplus <sup>TM</sup>	<b>54.3</b> (22.7)	<b>69.2</b> (41.1)	<b>50.1</b> (9.3)	<b>65.1</b> (11.1)

### 4.3.4 Silicon

The relative efficiency of 4 different extractants used to analyse the plant available silicon contents of the soils of the project have been outlined above (Section 3.5). The 0.1 M CaCl<sub>2</sub> extractant was found to be most effective; values less than a threshold value of 20 g / g is thought to indicate soils that are deficient in silicon (Fox *et al.* 1967).

There were no statistically significant differences among the extractable silicon contents determined for all the soil conditioner – fertiliser treatments of the Innisfail Clay (Table 4.12). The High Minplus<sup>TM</sup> treatments had large standard deviations, but may indicate a slight trend to higher extractable silicon contents.

**Table 4.12** Mean plant available silicon contents ( g / g, or, ppm), and standard deviations shown in parentheses, of surface soils of each soil conditioner – fertiliser treatment of the field trial at Johnstone College of TAFE, Innisfail. Weak acid (0.1M CaCl<sub>2</sub>) extraction; mean values are derived from 4 replicates for each treatment. Source: Burton (1999).

	Plant available silicon ( g / g)			
	Nil fertiliser	Q Phos	Superphosphate	DAP
Nil amendment	<b>15.8</b> (1.2)	<b>16.9</b> (2.3)	<b>16.3</b> (1.1)	<b>16.7</b> (1.2)
Lime	<b>17.4</b> (1.8)	<b>15.7</b> (2.1)	<b>16.1</b> (2.4)	<b>16.1</b> (1.0)
Cement	<b>18.7</b> (2.5)	<b>18.4</b> (2.0)	<b>19.0</b> (1.6)	<b>18.1</b> (0.7)
Low Minplus <sup>TM</sup>	<b>16.7</b> (1.9)	<b>16.4</b> (0.9)	<b>16.3</b> (1.9)	<b>16.5</b> (0.3)
High Minplus <sup>TM</sup>	<b>22.1</b> (3.5)	<b>23.8</b> (5.7)	<b>21.2</b> (4.4)	<b>22.2</b> (5.5)

## 4.4 Changes in plant growth induced treatments

### 4.4.1 Legume responses to soil treatments

Above average rainfall was received at the experimental site in every month, except for May 1999 (Fig. 4.2), from the time that the soil conditioners were applied (October 1998) until the harvest at maturity (July, 1999). Intermittent periods of 1–3 weeks of prolonged hot and dry conditions occurred throughout the experimental period.

One of these dry periods began in the week before the fertilisers were applied and the legumes were sown, and it had a major impact on the establishment of *A. pinto*, which grows well near the experimental plots (Fig. 4.7). Despite above average rainfall in the period prior to planting the legumes, a 3 week period of hot dry weather immediately followed planting which desiccated the *Arachis pinto* cuttings and none of them established. Germination of the sown seed was equally poor. A subsequent test on the seed indicated a 2% germination rate. Despite this poor start, *A. pinto* did establish poorly on the plots treated with cement, but it had virtually disappeared by the harvest at maturity.

In the first growing season, *Aeschynomene americana* produced much higher above ground standing crops than any of the other legumes in all the plots. It established rapidly and grew well in all the treatments (Fig. 4.8), but was more prolific in the cement and High Minplus<sup>TM</sup> treatments.

*S. guianensis* also established rapidly in most plots (Fig. 4.9), with the best overall result being in the High Minplus<sup>TM</sup> plots. *C. pubescens* appeared to establish quite well (Fig. 4.9), especially in the Control and High Minplus<sup>TM</sup> treatments but, as a consequence of its inability to compete with the vigorous grass and dominant *A. americana*, it did not grow on well to maturity. No *D. virgatus* specimens were found in any of the harvested materials, although occasional plants were observed in isolated patches of plots throughout the experiment.

**Figure 4.7** Despite the lack of establishment of *Arachis pinto* cv Amarillo (Pinto, or, forage peanut) in the experimental plots, it does grow well under strongly shaded and heavily grazed conditions in the paddock adjacent to the experimental area at the Johnstone College of TAFE, Innisfail.





**Figure 4.8** Tall *Aeschynomene americana* (cv Glen Joint Vetch) legumes in the vigorously growing *Brachiaria decumbens* (signal grass) pasture at maturity, Johnstone College of TAFE, Innisfail, July 1999. (Photograph by F. Jacintho).



**Figure 4.9** By March 1999, the introduced legumes had established to different extents, and with different vigour, in the dense *Brachiaria decumbens* (signal grass) pasture at the Johnstone College of TAFE, Innisfail. The fine trifoliolate leaves of *Stylosanthes guianensis* (Cook stylo) and the darker, broader trifoliolate leaves of *Centrosema pubescens* (Cardillo centro) are evident in the centre of the photograph. The larger, bipinnate leaves of *Aeschynomene americana* (Glen Joint Vetch) have entered the left side of the photograph. (Photograph by F. Jacintho).



## 4.4.2 Plant productivity

### Pasture production

An increase was observed in plant growth from the order of 5 t/ha of dry matter at establishment (March 1999 harvest) to the order of 15 t/ha at maturity (July 1999 harvest), with the increase relatively uniform across treatments (Fig. 4.10).

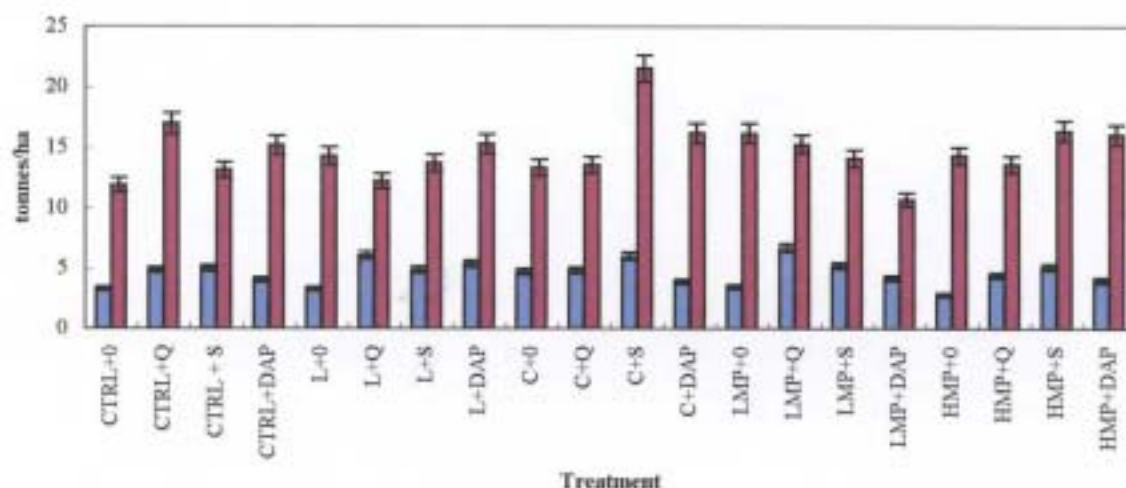


Figure 4.10 The average dry weights of the above ground standing crop ( t/ha) determined from 4 replicates of each soil conditioner – fertiliser treatment of the field trial at the Johnstone College of TAFE, Innisfail. The left column of each pair of histograms indicates the crop mass at establishment (March 1999 harvest), and the right column indicates the crop mass at maturity (July 1999 harvest). Error bars indicate 95% confidence intervals. Source: Burton (1999).

### Abbreviations for treatments:

CTRL: control = nil soil conditioner, L: lime, C: cement, LMP: low Minplus™ (2.5 t/ha), HMP: high Minplus™ (25 t/ha); +0: control = with nil fertiliser, +Q: with Q Phos (rock phosphate), +S: with superphosphate, +DAP: with DAP (diammonium phosphate)

### Pasture composition

Although the pasture sward was dominated by *Brachiaria decumbens* grass at both harvests, there was a significant change with time in the relative abundances of the introduced legumes and “other species” (mainly weeds, including: *Crotalaria* sp., *Celosia* sp., *Passiflora foetida*, *Mitracarpus* sp., *Solanum* sp., *Ipomoea* sp.; Burton 1999). At establishment the “other species” had produced a larger above ground standing crop than the legumes (Fig 4.11). This situation was reversed by maturity (Fig 4.11), largely through the maturing of the *A. americana* (Fig 4.8); the decrease in “other species” may be the result of competition, or it may reflect the relatively short life-spans of many of the plants that are recognised as weeds in tropical pastures.



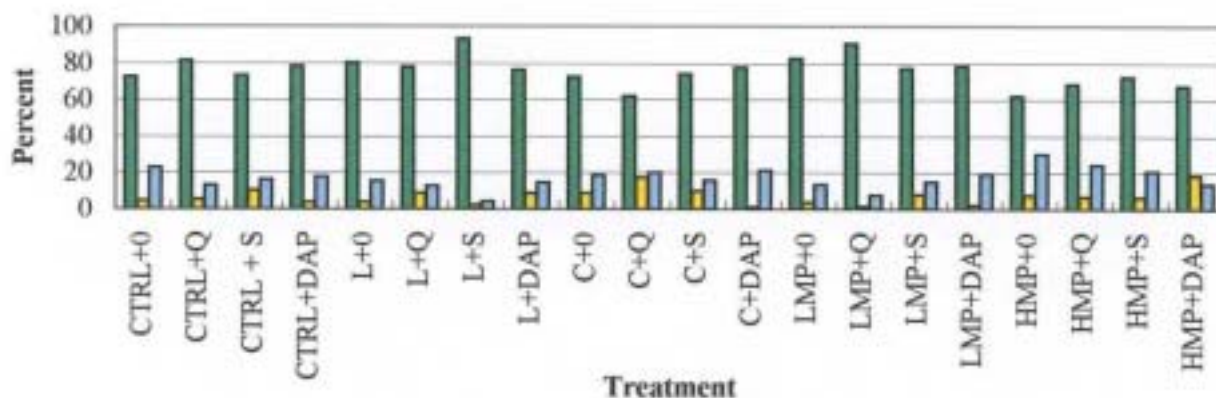


Figure 4.11 Relative proportions of pasture components at the time of establishment (March 1999 harvest) across all the soil conditioner – fertiliser treatments of the field trial at the Johnstone College of TAFE, Innisfail. In each group of 3 histograms, the left column indicates the mean percentage of *Brachiaria decumbens* (signal grass), the middle column indicates the mean percentage of all the sown legumes, and the right column indicates the mean percentage of “other species”, predominantly weeds and the pre-existing legumes. Each column represents the mean of 4 replicates for each treatment. Source: Burton (1999).

Abbreviations for treatments:

CTRL: control = nil soil conditioner, L: lime, C: cement, LMP: low Minplus™ (2.5 t/ha), HMP: high Minplus™ (25 t/ha); +0: control = with nil fertiliser, +Q: with Q Phos (rock phosphate), +S: with superphosphate, +DAP: with DAP (diammonium phosphate)

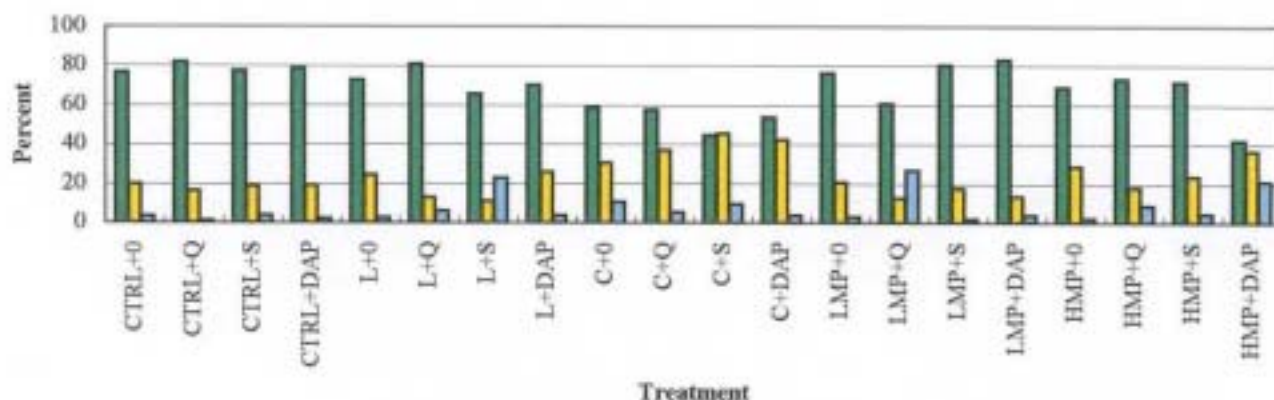


Figure 4.12 Relative proportions of pasture components at maturity (July 1999 harvest) across all the soil conditioner – fertiliser treatments of the field trial at the Johnstone College of TAFE, Innisfail. In each group of 3 histograms, the left column indicates the mean percentage of *Brachiaria decumbens* (signal grass), the middle column indicates the mean percentage of all the sown legumes, and the right column indicates the mean percentage of “other species”, predominantly weeds and the pre-existing legumes. Each column represents the mean of 4 replicates for each treatment. Source: Burton (1999).

Abbreviations for treatments:

CTRL: control = nil soil conditioner, L: lime, C: cement, LMP: low Minplus™ (2.5 t/ha), HMP: high Minplus™ (25 t/ha); +0: control = with nil fertiliser, +Q: with Q Phos (rock phosphate), +S: with superphosphate, +DAP: with DAP (diammonium phosphate)

#### *Plant production at establishment (3 months after planting)*

Most of the treatments produced 4 – 5 t/ha of dry plant material at the time of establishment (Fig. 4.11). The greatest plant growth at the time of establishment was in the Lime + Q Phos, Low Minplus<sup>TM</sup> + Q Phos, and Cement + Superphosphate treatments (Fig. 4.11).

At the other extreme, the least amount of above ground standing crop was found in the High Minplus<sup>TM</sup> + Nil fertiliser treatment, which produced less plant material than the Control + Nil fertiliser treatment (Fig. 4.11).

#### *Plant production at maturity (6 months after planting)*

At maturity, the least amount of plant dry matter was produced by the Low Minplus<sup>TM</sup> + DAP treatment, which was less than that produced by any of the Control treatments that had no soil conditioners added (Fig. 4.12).

All the other treatments produced above ground standing crop masses that were greater than the plant yield from the Control + Nil fertiliser treatment (12 t /ha; Fig. 4.12). Only the Cement + Superphosphate treatment produced more plant mass (22 t/ha) than did the most productive of the Control treatments, which was the Control + Q Phos plots (17 t/ha; Fig 4.12).

The strong plant growth responses to the Control + Q Phos combination was unexpected in that Q Phos has the lowest solubility of all the fertilisers used. However, none of the other treatments involving Q Phos showed the same kind of plant response. Higher growth rates were anticipated in the DAP treatment combinations because of the higher solubility of this fertiliser, but only the Lime + DAP treatment produced a high above ground standing crop (Fig 4.12).

At the time of establishment, all the nil soil conditioner (Control +) treatments had similar proportions of legume in the above ground standing crop (except for the Control + Superphosphate treatment), which was lower than the masses of plant material produced by all the other treatments, as was expected (Fig 4.12).

At maturity, all the Control treatments had produced similar above ground standing crops, and they exceeded the plant production from the Lime + Superphosphate, Lime + Q Phos, and Low Minplus<sup>TM</sup> + DAP treatments (Fig 4.12). The High Minplus<sup>TM</sup> and Cement treatments produced significantly more legume mass at maturity than did the other treatments; the latter did not differ from the Controls (Fig 4.12; Table 4.13).

**Table 4.13 Mean total dry above ground standing crop (t/ha) produced by each soil conditioner treatment on establishment ('est.' = March 1999 harvest) and maturity ('mat' = July 1999 harvest). Data are averaged for each soil conditioner over all fertiliser treatments (n = 16). Source: Burton (1999).**

Soil conditioner	Total above ground standing crop		<i>Brachiaria decumbens</i>		All legumes	
	est.	mat.	est.	mat.	est.	mat.
<b>Control</b>	4.3 b	14.3 a	3.5 b	11.5 a	0.2 a	2.5 b
<b>Lime</b>	4.9 b	13.9 a	4.1 a	11.6 a	0.3 a	2.0 b
<b>Cement</b>	4.9 b	16.2 a	3.4 b	8.3 a	0.6 a	6.7 a
<b>Low Minplus<sup>TM</sup></b>	4.9 a	14.1 a	4.3 a	10.9 a	0.2 a	2.4 b
<b>High Minplus<sup>TM</sup></b>	4.1 b	15.1 a	2.8 b	11.6 a	0.4 a	5.7 a

Means in a column followed by the same letter are not significantly different.

There was a significantly greater production of above ground standing crop of *B. decumbens*, hence of the total plant mass produced at establishment in response to the application of phosphatic fertilisers, but it had disappeared by the time of the harvest at maturity (Table 4.14). Conversely, at maturity, significant differences in the above ground standing crop of the legumes had developed in response to the soil conditioners (Table 4.14). Differences in the legume masses were too small, however, to influence the mass of the total above ground standing crop at maturity.

**Table 4.14** Summary of effects of soil conditioner and fertiliser treatments imposed on the field trial at the Johnstone College of TAFE, Innisfail. Source: Burton (1999).

Test variable	Harvest <sup>++</sup>	The effect of:		
		Soil conditioner	Fertiliser	Interaction
<b>Total mass of above ground standing crop</b>	March 99: est.	n.s.	**	n.s.
	July 99: mat.	n.s.	n.s.	n.s.
<b>Mass of <i>Brachiaria decumbens</i></b>	March 99: est.	n.s.	**	n.s.
	July 99: mat.	n.s.	n.s.	n.s.
<b>Mass of all legumes</b>	March 99: est.	n.s.	n.s.	n.s.
	July 99: mat.	**	n.s.	n.s.
<b>Plant available phosphorus in soil</b>		***	**	n.s.

n.s. (no significant effect); \* (0.05 > P > 0.01); \*\* (0.01 > P > 0.001); \*\*\* (P < 0.001)

++ 'est.' = Time of establishment of legumes; 'mat.' = Maturity of legumes.

# 5. Identifying constraints to plant growth: the Cape Flattery Sand

## 5.1 Research approach

### 5.1.1 Research questions

Many of the highly weathered soils of the humid tropics of northeastern Australia exhibit important constraints to plant growth, including:

- low cation exchange capacity of the soil, which reduces the capability of the soil to retain cations against leaching processes and to supply cations to plants,
- low basic cation supply in the soil leading to deficiencies or imbalances in supply of macronutrients that are essential for adequate plant growth (especially calcium, magnesium, and potassium),
- strong soil acidity,
- strong phosphate fixing capacity of particular soils.

Initial detailed studies of the capacity of Minplus™ rock dust to overcome some of these constraints were focused on the soils of the Innisfail and Tully Series (Brown 1998), and on the Pin Gin Series (Smallwood 1998). With the establishment in 1998 of a field trial site on the acidic, clay-rich Innisfail Clay, which exhibits all the constraints to plant growth listed above, much more attention has been paid to the properties this soil and the consequences of Minplus™ applications to it.

Subsequently, efforts have been made to determine the nature of the changes that Minplus™ can effect in a neutral, siliceous sand soil in coastal North Queensland at the Cape Flattery Silica Sand Mine, 360 km north of Cairns. The results of the research may be used as an aid in developing revegetation strategies following sand mining.

The soil and plant nutritional research on the Cape Flattery Sand and the Innisfail Clay that is reported on in this and the following chapter has attempted to answer specific questions of general application to the highly weathered soils of the humid tropics:

- What are the main nutritional deficiencies or other constraints to plant growth presented by the soil – calcium deficiency, magnesium deficiency, imbalances in the calcium : magnesium ratio, soil acidity, or phosphate fixation?
- Can Minplus™ applications overcome these constraints and, if so, to what extent?
- How does Minplus™ function in the soil to effect improvements in plant growth?
- Do Minplus™ applications influence the status of calcium, magnesium, phosphorus, and aluminium in the soil and their uptake by plants? (The answer to this question requires foliar tissue analyses for which plant materials have been collected, but have not yet been analysed).

### 5.1.2 The role of pot trials

The pioneering studies of Brown (1998) and Smallwood (1998) contributed heavily to formulating the research approach adopted in the present study. Their results were influenced by factors whose significance could not be addressed at the time: the use of a soil modifier at concentrations that were too high and produced toxic effects, watering on demand and confounding the impacts of water and nutrient supplies on plant growth, and using an indicator plant (silk sorghum) whose foliar symptoms of nutrient deficiencies are not as well understood as those of the tomato. Nevertheless, their studies provided valuable understandings that have led to the research approach outlined below.

Pot trials were set up to analyse and interpret the various responses of indicator plants that show relative differences in growth to the application of increasing amounts of Minplus™ (applied at the equivalents of 0, 2.5, and 25 t/ha) to the Cape Flattery Sand and the Innisfail Clay. These application rates were chosen to match the treatments applied to the field experiment at the Johnstone College of TAFE, Innisfail (Chapter 4, above), for 3 reasons. They represent:

- an untreated experimental control (0 t/ha),
- a commercial application rate for Minplus™ and lime commonly used in the area (2.5 t/ha),
- a high rate (25 t/ha) to trigger measurable responses within the short time frame of the study.

Different additives were left out or added to the experimental pots (nutrient omission or addition trials) to provide a sound basis for determining the processes whereby the soil conditioner is able to modify the properties of the soil and promote enhanced plant growth responses.

An attempt is made in the present chapter to provide answers to the research questions set out above from an analysis of the results from nutrient omission pot trials on the Cape Flattery Sand. The results of a nutrient addition pot trial on the Innisfail Clay are treated in Chapter 6, below. The plant growth responses and the soil characteristics of the 2 strongly contrasting soils are discussed in Chapter 7 in the context of understanding the mechanisms that control the soil reactions and plant growth responses to Minplus™ applications.

## **5.2 The Cape Flattery Sand**

### **5.2.1 Diagnosing plant growth disorders from nutrient omission trials**

A nutrient omission pot trial approach has been used to identify growth differences of plants established in sands treated with nil, low, and high rates of application of Minplus™ and supplemented by nutrient solutions of different compositions. This approach uses the differential growth of a test plant to make a bioassessment of the nature and degree of the deficiency of specific macronutrient elements in the soil, and of the extent to which those nutrient deficiencies may be overcome by Minplus™ applications to the soil.

For example, if the soil and supplementary nutrient solution contained all the essential nutrients needed to ensure optimal growth of a plant, then the growth of the indicator plant would lie in the 'Adequate zone' of Fig 4.1 (Section 4.1, above). Omitting an essential element from the nutrient solution will limit plant growth, which can then be no greater than that allowed by the content of the element of interest in the soil. The relative importance to plant growth of an essential element is inversely related to the magnitude of growth responses of an indicator plant to the overall nutrient supply that is available from the combination of soil and supplementary nutrient solution from which the particular essential element has been omitted.

Therefore, differences in the degree of stunting of plants grown in soils treated with a complete nutrient solution and with a range of nutrient solutions that lack single essential elements will reflect the relative availability of the omitted elements in the soil.

The nutrient omission approach may be repeated using soil to which an amendment such as Minplus™ has been applied. Comparing the resultant differential plant growth with that in the untreated soil will indicate the extent to which the soil conditioner has overcome the nutrient deficiencies inherent in the soil.

The Cape Flattery Sand contains very little colloidal material to sorb or otherwise interact with any nutrients released from the Minplus™ amendments. It offers an ideal rootzone medium for testing the extent to which Minplus™ applications to the sand may overcome any nutrient deficiencies that are identified.

### **5.2.2 The study area and soils**

Cape Flattery is located at 145° 20' E and 14° 50' S in coastal lowlands on the eastern side of Cape York Peninsula, approximately 450 km north of Innisfail, and 40 km north of Cooktown, North Queensland. The fine grain-size and very high silica content of the sand in the large aeolian sand dunes of Cape Flattery has led to the establishment of a medium scale sand mining operation in the area. The naturally clean silica sand is mined, washed, size-sorted, and shipped to Japan for glass manufacturing.

Like the Innisfail area, the climate of Cape Flattery is humid tropical, with a summer-dominant rainfall of approximately 1600 – 1800 mm per year, of which over 75% falls in the wet season between January and April.

The sands of the Cape Flattery dunefields consist of well sorted, medium to fine grained sands that consist of 91 - 99 % silica (Pye 1982a, b). Their soils represent a harsh environment for plant growth with a very low nutrient content, poor water retention, and high level of wind and water erosion (Pye 1982). The vegetation varies from low, open heath to closed forest in response to exposure to on-shore winds and differences in soil profile drainage (Pye and Jackes 1981).

Deep podzol soil profiles show many of the characteristics described by Thompson (1981, 1983, 1992) from similar dunefields in southeastern Queensland, and by soils of the Kaygaroo and Kurrimine Series that have formed in old, stranded beach ridges of the Innisfail – Tully area (Murtha 1986). The soils present prominent, organic matter-enriched, dark coloured A1 horizons, overlying thick (0.5 – 8+ m), white, bleached, sandy A2 horizons, and B horizons of heavier texture in which iron, aluminium, and organic matter have accumulated.

Natural erosion and mining of the sand dunes at Cape Flattery has disrupted soil profiles and extensive areas of clean, white sandy subsoils (A2 horizons) remain, which are bare of any significant plant cover (Fig. 5.1). Some topsoil is returned to the mined areas in order to begin to re-establish ground cover plants, but the soil resource is scarce. Conventional fertilisers are used at the time of planting to supplement the extremely limited soil nutrient supplies. Applying Minplus™ has the potential to address some of the plant nutritional requirements of the revegetation programs of the disturbed areas.

The use of fertilisers or soil conditioners that are specific to the nutrient needs of the revegetation species makes sense economically and environmentally. While Minplus™ applications will not eliminate the need for conventional N-P-K fertilisers, they may decrease the need for fertiliser requirements by improving a range of soil properties. The results of the leaching experiments discussed in Chapter 8, below, suggest that the ameliorating influence of Minplus™ dressings might persist for much longer in the soil than the readily soluble conventional fertilisers currently used at the Cape Flattery Silica Sand Mine.



**Figure 5.1** Natural erosion of sand dunes in the Cape Flattery area exposes clean, bleached sands of thick A2 horizons of podzol soils. Thin topsoils (A1 soil horizons) have accumulated some organic matter from decomposing plant litter on the soil surface. (Photograph supplied by Natural Resource Assessments Pty Ltd, Cairns).

### 5.2.3 Materials and methods

#### *Soil preparation: Cape Flattery Sand*

Approximately 1 t of white, sandy A2 horizon material from the Cape Flattery Sand were transported by truck and barge to the Cairns Campus of James Cook University where the studies reported below were performed (Horner 2000).

The soil was air-dried at James Cook University, Townsville, sieved to less than 2 mm, and mixed in a clean, motorised cement mixer with Minplus™ to produce the equivalents of application rates of 0, 2.5, and 25 t/ha (nil, low, and high rates respectively) in the pots.

Each of the bulk soil mixtures, including the untreated soil, was moistened to a glistening state, which approximates to being wet to field capacity and allows soil chemical reactions to proceed. The moist bulk samples were allowed to incubate for 10 weeks in sealed plastic bags at room temperature and in the dark to inhibit fungal growth. The untreated soil was incubated to account for any changes induced by the incubation process in the bioassessments of plant growth responses to the Minplus™ treatments.

A previous study suggested that a longer incubation period (up to 12 months; Gillman 1980) would have been produced stronger soil reactions. But the time constraints of the project did not allow for such an approach. Minplus™ applications rates were selected to show plant growth responses to:

- untreated soil (0 t of Minplus™ / ha ), which was included to ensure that any possible effects of incubating the Minplus™-treated soils would also be reflected in the experimental controls;
- soil treated with a farmer-determined application rate of lime and Minplus™ that is commonly used in the area (equivalent to 2.5 t Minplus™ / ha);
- soil treated with a high application rate (equivalent to 25 t/ha) in order to obtain useful results within the limited time-frame of the present study.

Moist soil was directly weighed into the round experimental pots (9.2 cm diameter and 13.5 cm high) following the incubation period. Similar soil masses per pot ensured that there were consistent volumes of soil for the plant roots to exploit in each treatment.

#### *Nutrient solutions*

Plant nutrients were supplied to each of the sand-Minplus™ mixtures from a 'Brownell nutrient solution' (Brownell 1979), which is used experimentally in water culture solutions to deliver all the essential elements required for adequate growth of plants (Table 5.1). Further, pots of each soil were treated with a partial Brownell solution from which one of the essential macronutrient elements was omitted. The omitted elements were: nitrogen, phosphorus, potassium, calcium, magnesium, sulphur and iron. In order to achieve this goal, the composition of the Brownell solution was adjusted to make up a series of solutions that lacked only one essential element for plant growth. The ionic balances of the partial solutions were maintained by adjusting the amounts of the other elements (Table 5.1).

**Table 5.1** Solutions used to prepare 1 litre of complete or partial Brownell nutrient solution. Numbers refer to the number of millilitres of source solutions of 1 Molar concentration that are required to produce one litre of the plant nutrient solution. Source: Brownell (1979).

1 Molar source solutions	Complete plant nutrient solution	Partial plant nutrient solutions lacking one essential element						
		– N	– P **	– K	– Ca **	– Mg **	– S	– Fe
KNO <sub>3</sub>	5	-	5	-	5	5	5	5
Ca(NO <sub>3</sub> ) <sub>2</sub>	5	-	5	5	-	5	5	5
MgSO <sub>4</sub>	2	2	2	2	2	-	-	2
KH <sub>2</sub> PO <sub>4</sub>	1	1	-	-	1	1	1	1
KCl	-	5	1	-	-	-	-	-
CaCl <sub>2</sub>	-	5	-	-	-	-	-	-
Na <sub>2</sub> SO <sub>4</sub>	-	-	-	-	-	2	-	-
NaNO <sub>3</sub>	-	-	-	1	-	-	-	-
NaH <sub>2</sub> PO <sub>4</sub>	-	-	-	5	10	-	-	-
MgCl <sub>2</sub>	-	-	-	-	-	-	2	-
36.5 g/L Fe-EDTA + Micro-nutrients	1	1	1	1	1	1	1	-
++	1	1	1	1	1	1	1	1

+ 36.5 g / L of Fe-EDTA contains 5 mg of iron as CH<sub>2</sub>.N(CH<sub>2</sub>.COO)<sub>2</sub>]<sub>5</sub>FeNa.

++ Micronutrient supplementary solution is required – see Table 5.2.

\*\* Partial solutions used at 50% dilutions in the pot trial on the Innisfail Clay (Section 6.2).

**Table 5.2** Compounds used to supply micronutrient elements to plant nutrient solutions. Source: Brownell (1979).

Element	Compound	Mass of compound required to make up 1L of stock solution	Final concentration of stock solution	
			ppm	M
Boron	H <sub>3</sub> BO <sub>3</sub>	2.86 g	4.98 x 10 <sup>-4</sup>	46.0
Manganese	MnCl <sub>2</sub> .4H <sub>2</sub> O	1.81 g	4.99 x 10 <sup>-4</sup>	9.1
Zinc	ZnSO <sub>4</sub> .7H <sub>2</sub> O	0.22 g	4.97 x 10 <sup>-5</sup>	0.76
Copper	CuSO <sub>4</sub> .5H <sub>2</sub> O	0.08 g	1.97 x 10 <sup>-5</sup>	0.31
Molybdenum	NaMoO <sub>4</sub> .2H <sub>2</sub> O	0.025 g	9.59 x 10 <sup>-6</sup>	0.10



### *Indicator plants*

Tomato (*Lycopersicon esculentum* Mill., var. Grosse Lisse) was chosen as an indicator of plant growth in the studies on both the Cape Flattery Sand and Innisfail Clay for the following reasons. The tomato has:

- small seeds so that the plant growth in the pot trial would relate to the nutrients the plant received from the soil, rather than from seed reserves from large seeds;
- rapid growth under the ambient conditions of the study: May – July 1999 at Townsville (Innisfail Clay), and December 1999 – January 2000 at Cairns (Cape Flattery Sand);
- clear foliar symptoms of nutrient deficiency for which there are published guides (see, for example, Bould *et al.*, 1983; Gupta, 1983; Barker 1985; Kretschmer and Snyder, 1989; Weir and Cresswell 1993).

For the study on the Cape Flattery Sand, a native grass (*Digitaria leucostachya*) was also selected as an indicator plant from several local grass species at the Cape Flattery heathlands. This was because of its potential use in revegetation programs at the minesite, and because it recorded the highest germination rate among the local grasses in a pilot study (Horner 2000).

### *Watering regimes: Cape Flattery Sand*

Water and nutrients were supplied exclusively to the plants through the complete and partial Brownell nutrient solutions, and water only to the control group.

In order to reduce the influence of fluctuating soil moisture regimes on the growth rates of the indicator plants, and to avoid flushing plant nutrients from the pots, the water content of the potted soils was maintained at 80–100% of field capacity (Miller and Donahue, 1995, p. 615). Pot masses were closely monitored throughout the experiment and the plants were watered with an appropriate nutrient solution when the pot weight fell below the critical mass equivalent to the mass of (pot + the soil + water equivalent to 80% of the field capacity of the soil).

On clear sunny days ‘watering’ occurred approximately twice a day to prevent wilting. On overcast or rainy days the pots were ‘watered’ once every 2–3 days. A more frequent ‘watering’ was found to cause ponding and seepage of solutions from the pots. Overflow or seepage was collected in saucers beneath the pots, and was recycled back into individual pots.

This approach to ‘watering’ was established in order to maintain the discrete influence of the complete or partial solution on plant growth within treatment groups.

In hindsight, however, the style of ‘watering’ has led to a confounding of the effects of soil moisture availability and nutrient availability because the most vigorously growing plants used the most water from the limited resources in the potted soils. The plants, although growing rapidly, also wilted most rapidly, and their ‘water supply’ was replenished the most frequently from the complete or partial Brownell nutrient solutions (with an unavoidable supplementation of the nutrients in the relevant solution). Hence, the unequal use of water by plants of different vigour has led to an uneven supply of nutrients from the applied solutions.

The linkage between water and nutrient supply has been overcome in the innovative experimental design adopted by Satimbre (2001) in which a double container has been used. A lower, disposable plastic container holds the nutrient solution of required composition, and is fitted with a plastic lid into which a hole has been cut that is just larger than the basal area of the slightly tapering pot. The base of the pot carrying the treated soil, covered with fine muslin to retain the soil, is placed in the hole in the lid of the lower nutrient reservoir. The height of the nutrient solution is adjusted so that it is free to enter the drainage holes in the base of the pot and diffuse, by capillary rise, up into the rootzone of the experimental plant. By topping up the level of the nutrient solution in the lower reservoir, the water status of the pot may be held constantly at 80–90% of field capacity for the life of the experiment. The nutrient reservoir is kept aerated by a small air pump (as is used in a home aquarium) and the air supply to the reservoirs is delivered at a slow, regulated volume through fine plastic tubing that is connected to the air supply line through hypodermic needles.

### *Experimental design*

The nutrient omission experiment was designed using two plants: tomato (*Lycopersicon esculentum* Mill., var. Grosse Lisse) and grass (*Digitaria leucostachya*) and one soil treated with 3 levels of Minplus<sup>TM</sup> (0, 2.5 and 25 t/ha) to which 9 nutrient treatments were applied. The nutrient treatments (Table 5.1) were:

- Complete Brownell solution containing all the essential plant nutrients (H+)
- Partial Brownell solution lacking nitrogen (N-)
- Partial Brownell solution lacking phosphorus (P-)
- Partial Brownell solution lacking potassium (K-)
- Partial Brownell solution lacking calcium (Ca-)
- Partial Brownell solution lacking magnesium (Mg-)
- Partial Brownell solution lacking sulphur (S-)
- Partial Brownell solution lacking iron (Fe-)
- No nutrient addition (water only)

Each treatment was replicated 5 times in a randomised block design:

2 plants x 3 Minplus<sup>TM</sup> levels x 9 nutrient solutions x 5 replicates = 270 treatments.

### *Experimental measurements*

Plant growth measurements were recorded weekly. For the tomatoes, plant height, petiole height, number of branches, number of leaves, and length of longest leaf were recorded. For the grasses the number of tillers, length of longest tiller, and width at broadest point of the longest tiller were recorded. Foliar disorders were recorded for both the tomato and grass. While making the measurements, any foliar symptoms of nutrient deficiencies were observed and recorded. To quantify the differences in the colours of foliar symptoms observed, the colours of the leaves were graded as, 1 (least) to 5 (most) purple, using Munsell Plant Colour Charts.

At the end of the 7 week experimental period (December 1999 – January 2000), the shoots and roots of both plant species were harvested and the roots were washed free of soil on a 2 mm sieve under gently flowing water. The shoots were harvested by cutting at 1 cm above the soil surface, and leaves were cut at the stem end of their petioles. All plant material was dried in a fan-forced oven at 70 °C for 48 hours.

Despite having made fortnightly measurements of plant growth parameters, ‘total plant biomass’ was used below as the best measurement that integrates the overall contribution of all the observed growth parameters.

### *Soil analyses*

Soil samples were collected at the end of the experiment from the pots that had produced the strongest, middle, and weakest plant growth responses within the 5 replicates of each Minplus<sup>TM</sup>-soil nutrient solution treatment. This reduced the number of samples for chemical analysis without reducing the variability inherent in the replicates.

All the soil samples were dried in a fan-forced oven for 24 hours at 40 °C. Soil chemical analyses followed the methods of Rayment and Higginson (1992) for soil pH, electrical conductivity, exchangeable basic and acidic cations, and plant available phosphorus extracted using 0.005 M sulphuric acid. The extraction of soluble silicon followed the method of Page et al. (1982), using calcium chloride as the extractant.

## 5.3 Plant growth responses to soil and nutrient solution differences: results

### 5.3.1 Plant biomass production

The tall, etiolated habit of the experimental plants (Fig. 5.2) is attributed to the lack of light in the shadehouse caused by heavily overcast or rainy conditions that prevailed for almost the entire growing period at the height of the 1999 – 2000 wet season in Cairns.

Nevertheless, the tomato and native grass plants produced similar trends in their mean dry total biomasses (shoots + roots) when grown in soils treated with 3 application rates of Minplus™ (0, 2.5, 25 t/ha), whose nutrient contents were supplemented by 9 different nutrient solutions.

The data for the soils to which no Minplus™ had been applied (Fig. 5.2 b, and the column on the extreme right of each part of Fig. 5.3) clearly show the extremely low potential for production of tomato and the native grass plants under natural conditions when water alone is supplied to the soil. Much improved plant production has resulted when the complete Brownell nutrient solution was applied (Fig. 5.2 a, and the column on the extreme left of each part of Fig. 5.3).

The partial solutions, each lacking one of the essential macronutrient elements, produced tomato or native grass biomass at some level between the foregoing extremes (Figs 5.4 a, d). Growth in the soils supplemented by the partial solutions lacking phosphorus (all 5 replicates of the tomato experiment died) and nitrogen was particularly poor. This indicates the extreme level of deficiency of nitrogen and phosphorus in the Cape Flattery Sand.

Foliar symptoms of severe nutrient deficiencies were evident in the tomato plants in all the treatments that had received no Minplus™, including: severe stunting to the point of plant deaths, chlorotic leaves with necrotic margins, curling of youngest leaves, and intense purpling on adaxial (underneath) surfaces of leaves and on stems. The grasses showed less severe symptoms which included: severe stunting, interveinal chlorosis and reddish purple margins on leaves, necrotic leaf tips, and sporadic small necrotic spots.

Growth responses of both plants were marginally better in the soils to which 2.5 t/ha of Minplus™ had been applied, especially in the tomatoes given the complete Brownell solution, (Figs 5.3 b, e). Tomato and grass plants grown in the nutrient solutions lacking nitrogen and phosphorus were still extremely stunted (Fig. 5.4), but, in contrast with the nil Minplus™ treatments, all the replicates survived. Symptoms of nutrient deficiencies were less evident and less severe, often being restricted to the older leaves. None of the tomatoes grown in the partial solutions lacking iron and sulphur showed any signs of nutrient deficiencies; neither did the native grass growing in the nutrient solutions lacking potassium, calcium, or magnesium (Figs 5.3 b, e). This indicates that the 2.5 t/ha application of Minplus™ was adequate to overcome some of the nutrient deficiencies that were evident in the untreated soil.

There were marked improvements in plant growth in the soils to which the high rate of Minplus™ had been applied (Figs 5.3 c, f; Fig. 5.4). Only the tomatoes and grasses grown in the heavily amended soil that was supplemented by partial Brownell solutions lacking nitrogen and phosphorus, and tomatoes supplemented by the solution lacking potassium, showed nutrient deficiency symptoms and produced biomasses significantly lower than those produced by plants supplemented with the complete Brownell solution.

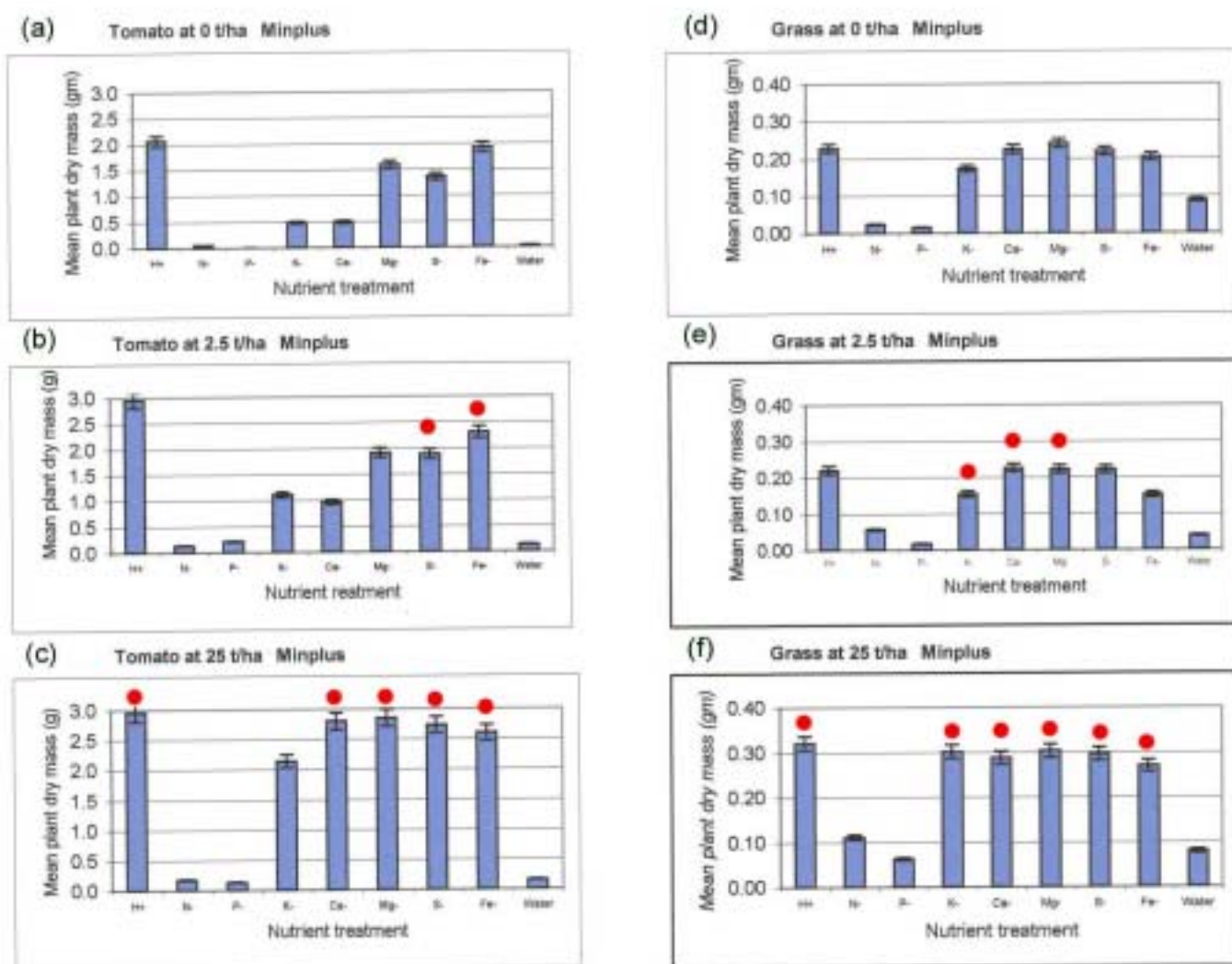
Only minor amounts of phosphorus is present in Minplus™ (Section 2.1.2). Nevertheless, there was a discernible increase in the growth of both tomato and native grass plants in the Minplus™ treatments that were supplemented with the partial solution lacking phosphorus. The bioassessment approach adopted in the present study indicates that the improved plant growth in the partial solutions lacking phosphorus must be derived from either the small amounts of phosphorus derived directly from the Minplus™ applications, or from other changes (such as increased micronutrient contents, or enhanced water-holding capacity of the soil) stimulated by the high rates of Minplus™ application.



**Figure 5.2** Growth responses at time of harvest of tomato plants grown in the Cape Flattery Sand with different rates of Minplus™ (0 M+ = nil, 2.5 M+ = 2.5 t/ha, 25 M+ = 25 t/ha of Minplus™) and different nutrient solutions whose compositions are shown in Table 5.1.

**Nutrient solutions used:**

- (a) complete Brownell solution, (b) water only, (c) partial solution lacking calcium,
- (d) partial solution lacking potassium.



**TOMATO:** *Lycopersicon esculentum*

**GRASS:** *Digitaria leptostachya*

Figure 5.3 The mean dry total biomasses (shoots + roots) of tomato (left) and native grass (right) plants grown in the Cape Flattery Sand under different combinations of Minplus<sup>TM</sup> application rates and plant nutrient solutions.

- (a) Tomatoes, no Minplus<sup>TM</sup> amendment; (d) Native grass, no Minplus<sup>TM</sup> amendment;  
 (b) Tomatoes, 2.5 t/ha Minplus<sup>TM</sup> applied; (e) Native grass, 2.5 t/ha Minplus<sup>TM</sup> applied;  
 (c) Tomatoes, 25 t/ha applied; (f) Native grass, 25 t/ha applied.

The sandy soil was treated with 3 application rates of Minplus<sup>TM</sup> (0, 2.5, 25 t/ha), whose nutrient contents were supplemented by 9 different nutrient solutions (shown from the left): complete Brownell solution (H+); partial Brownell solutions that lack N, P, K, Ca, Mg, S, Fe; and water. Dots above a column indicate that no foliar symptoms of nutrient deficiency were evident on any of the 5 replicates within the treatment. Error bars indicate 95% confidence intervals.

Source: Horner (2000).

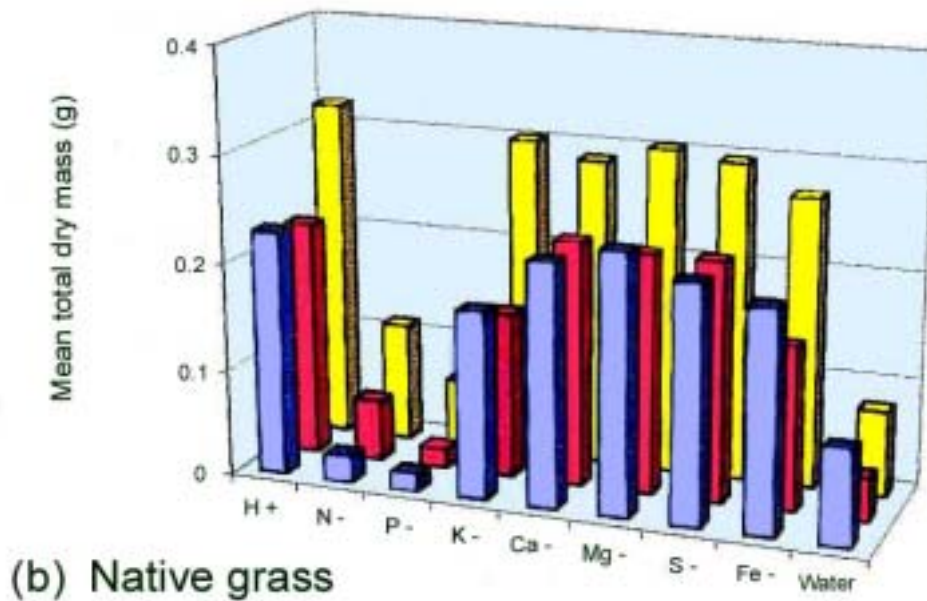
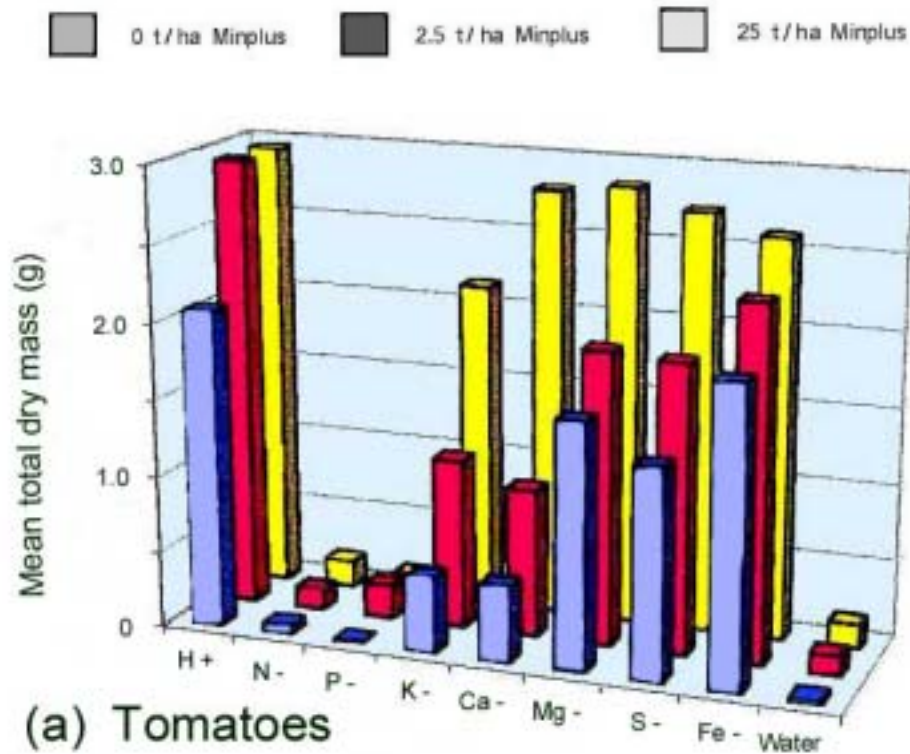


Figure 5.4 Mean dry total plant biomass (shoots + roots) of tomato and grass plants grown in pots of the Cape Flattery Sand under different combinations of Minplus<sup>TM</sup> and plant nutrient solutions.  $n = 5$  for each column. The statistical significance of the differences in plant growth responses is shown graphically in Fig. 5.3 a-f.

The soil was treated with 3 application rates of Minplus<sup>TM</sup> (0 t Minplus<sup>TM</sup> / ha = front row of columns; 2.5 t Minplus<sup>TM</sup> / ha = middle row of columns; 25 t Minplus<sup>TM</sup> / ha = back row of columns), whose nutrient contents were supplemented by 9 different nutrient solutions (shown from the left): complete Brownell solution (H+); partial Brownell solutions that lack N, P, K, Ca, Mg, S, Fe; and water. Source: Horner (2000).

### 5.3.2 Nutrient deficiencies

Nitrogen and phosphorus were found to be the most severely limiting nutrients to the growth of tomatoes or the native grass in the Cape Flattery Sand (Fig. 5.4). The responses of the plants supplemented by the partial solutions lacking nitrogen and phosphorus were severely stunted and chlorotic, and the tomatoes all died in the absence of both phosphorus and Minplus<sup>TM</sup> in the sand.

Potassium and calcium were the next most limiting elements for tomato growth in the soil, as plants grown under the solutions lacking these elements were chlorotic, stunted, and produced low total dry masses compared to the plants under the complete nutrient solution (Fig. 5.3 a). Magnesium, sulphur and iron deficiencies were only moderate constraints to tomato growth in the sandy soil. Tomato plants grown under the partial solutions lacking Mg, S, and Fe showed little stunting of growth compared to the plants grown under the complete nutrient solution (Fig. 5.3 a), and displayed only moderate chlorosis in the leaves.

It is well known that there may be considerable difference in the form of expression of nutrient deficiency symptoms in different plants, even in different cultivars of the same species (Wallace 1961; Bould *et al.* 1983; Grundon *et al.* 1997). Hence, it is not surprising that the native grass, *Digitaria leptostachya* should display slightly different nutrient deficiency symptoms from the tomatoes grown in the Cape Flattery Sand. There has been considerable debate about the phosphorus requirements of grasses, with suggestions that grasses may respond more slowly to phosphates (Troeh and Thompson, 1993), and be less sensitive to soil changes (Russell, 1978). Nitrogen and phosphorus are the nutrients most severely limiting grass growth which was only moderately stunted in the absence of potassium in the supplementary nutrient solution (Fig. 5.3 d). None of the other elements had any significant effect on grass biomass production compared with growth supplemented by the complete nutrient solution.

### 5.3.3 Nutrient deficiencies and Minplus<sup>TM</sup> applications

All the tomato and grass plants grown in the absence of Minplus<sup>TM</sup> exhibited foliar symptoms of nutrient deficiencies of varying degrees of intensity (Fig. 5.3 a, d).

With an application of only 2.5 t/ha of Minplus<sup>TM</sup>, the foliar symptoms of nutrient deficiencies disappeared in the tomatoes grown in the absence of sulphur and iron in the supplementary nutrient solutions, and in the grasses grown in the absence of potassium, calcium, and magnesium (Figs 5.3 b, e).

Stunted growth and other foliar symptoms of nutrient deficiencies in calcium, magnesium, sulphur, and iron in tomatoes were overcome by the high rate of application of Minplus<sup>TM</sup> (Figs 5.2 c and 5.3 c). Similarly, parallel symptoms of nutrient deficiency in all the elements, except for nitrogen and phosphorus, were alleviated by the high application rate of Minplus<sup>TM</sup> (Fig. 5.3 f).

The Cape Flattery Sand is an almost nutrient-free plant growth medium. It contains very little clay (considerably less than 10%, and occasionally less than 0.5%; Pye 1982 a, b) and the white, bleached sand contains almost no organic matter. When provided with a complete nutrient solution, the Sand supported adequate plant growth. When high application rates of Minplus<sup>TM</sup> were combined with the complete nutrient solution, the growth responses of both the tomatoes and native grass was considerably greater than those arising from the application of the nutrient solution alone (Fig. 5.4 a, b). The Minplus<sup>TM</sup> treatment is providing some other growth stimulation than that given by the essential plant macronutrients in the complete nutrient solution.

There are two probable explanations for the enhanced plant growth responses from the combination of Minplus<sup>TM</sup> and a complete nutrient solution. The Minplus<sup>TM</sup> may have provided a range of micronutrients beyond the 5 supplied in the complete nutrient solution (B, Mn, Zn, Cu, Mo; Table 5.2). Alternatively, the Minplus<sup>TM</sup> treatment has added a small amount of colloidal material to the matrix of the Cape Flattery Sand, which then had an enhanced capacity over that of the untreated Sand to retain moisture and nutrients in the rootzone of the indicator plants.



## 5.4 Soil responses to Minplus™: results

Changes induced by Minplus™ applications in selected chemical properties of the Cape Flattery Sand treatments to which water only had been added are listed in Table 5.3. In most cases, the low rate of Minplus™ application has not produced changes in soil chemical properties that are statistically significantly different from the corresponding values for the untreated soil. Except for the contents of exchangeable acidic cations in the soil, the high application rates of Minplus™ have induced statistically significant increases in all the analysed soil properties compared with the Nil and Low rates of the same amendment.

**Table 5.3** Selected mean chemical properties of the Cape Flattery Sand samples from different Minplus™ treatments in pots that had been watered only and had received no supplementary nutrient solutions. Source: Horner (2000).

Soil chemical property	Minplus™ application rates		
	Nil 0 t/ha	Low 2.5 t/ha	High 25 t / h
pH	6.64 b	6.45 b	6.97 a
Exchangeable Ca (cmol/kg)	0.08 c	0.37 b	0.40 a
Exchangeable Mg (cmol/kg)	0.03 c	0.08 b	0.14 a
Exchangeable K (cmol/kg)	0.03 b	0.04 ab	0.14 a
Exchangeable Na (cmol/kg)	0.06 b	0.08 ab	0.12 a
Total basic cations (cmol/kg)	0.02 b	0.57 ab	0.80 a
Total acidic cations (cmol/kg)	0.11 a	0.13 ab	0.06 b
ECEC (cmol/kg)	0.31 b	0.70 ab	0.86 a
Plant Available P ( g / g)	5.8 b	5.7 b	24.9 a
Extractable Si ( g / g)	3.6 c	4.1 b	5.1 a

Means followed by the same letter across a row are not significantly different ( $p < 0.05$ ).

### 5.4.1 Soil pH

The Cape Flattery Sand is neutral to only slightly acidic with a mean pH of 6.64 (Table 5.3). Even the high rate of Minplus™ application raised the soil pH by only 0.3 of a pH unit to a mean pH of 6.97. Burkett (1998) demonstrated an increase of 1.1 soil pH units (from 4.8 to 5.9) under a Minplus™ application of 25 t/ha to the Kurrimine Sand (Fig. 3.2), which has morphological properties similar to those of the Cape Flattery Sand.

### 5.4.2 Exchangeable basic cations

The amounts of calcium and magnesium brought into an exchangeable form by the application of 25 t/ha of Minplus™ to the Cape Flattery Sand are much smaller (0.40 and 0.14 respectively; Table 5.3) than those recorded for the Kurrimine Sand (1.75 and 2.44 respectively; Table 3.5). The exchangeable cation result may be a consequence of the difference in pH of the treated soils (pH of the Cape Flattery Sand = 6.97; Kurrimine Sand = 5.9), with the lower pH of the Kurrimine Sand enhancing the solubility of the cations.

The largest increase in the exchangeable basic cations induced by the increasing application rates of Minplus™ was in exchangeable calcium, which underwent a change of 0.33 cmol/kg (from 0.08 to 0.41 cmol/kg; Table 5.3).

The exchangeable magnesium increased by only 0.11 cmol/kg (Table 5.3), and not in the same proportion as the exchangeable calcium, even though the 2 elements are provided by Minplus™ in almost equal amounts (Table



2.1). However, at the high rate of application of Minplus™, the plants grown under the partial nutrient solution lacking Mg produced similar biomasses in the tomatoes and grass, and higher biomasses in the tomato plants than those grown in the partial nutrient solution that lacked calcium (Figs 5.2 c and 5.4).

Changes in the levels of exchangeable potassium and sodium were small compared to those in exchangeable calcium (Table 5.3), but were in keeping with the extent of the change effected by the use of a granitic rock dust on a sandy soil in Western Australia (Hinsinger *et al.* 1996)

### 5.4.3 Exchangeable acidic cations

While the high Minplus™ application rate produced a significant increase in the effective cation exchange capacity of the soil (ECEC; Table 5.3), the proportion of acidic cations on the exchange complex showed a significant and dramatic decrease (Table 5.4). Because the ECEC is quite low in this sandy, colloid-depleted soil, the decreasing proportion of acidic cations has had a minimal impact on raising the pH of the soil.

**Table 5.4** Soil cation contents of samples of the Cape Flattery Sand to which had been applied different amounts of Minplus™. Values are expressed as percentages of the effective cation exchange capacity (ECEC). Source: Horner (2000).

Cation	0 t/ha Minplus™	2.5 t/ha Minplus™	25 t/ha Minplus™
Calcium	26.1	52.1	46.5
Magnesium	9.6	11.4	16.2
Potassium	9.7	5.7	16.2
Sodium	19.0	11.9	13.9
Hydrogen and aluminium	35.5	18.4	7.0

### 5.4.4 Plant available phosphorus

Phosphorus and nitrogen were found to be the most limiting nutrients to plant growth in the Cape Flattery Sand (Section 5.3.4, above). Their deficiencies are also widespread constraints to plant growth in many humid tropical soils (Glendinning, 1999).

The amount of plant available phosphorus in the experimental soils increased significantly from an extremely low value (5.8 g / g) in the soils lacking Minplus™ to a low value (24.9 g / g) in the soils to which had been added 25 t/ha of Minplus™ (Table 5.3). Even the highest plant available phosphorus determined in the present study do not exceed the threshold value of 20 g / g thought by Bruce and Bruce (1972) to indicate a soil phosphorus level below which sugarcane would be expected to respond to phosphorus fertilisation.

Despite this increase in plant available phosphorus, some of the tomato and grass plants still exhibited symptoms of severe phosphorus deficiency, even in the soils that had received dressings of 25 t/ha of Minplus™. Minplus™ contains only a small total amount of phosphorus (0.3 %; Table 2.1), and this was still not enough plant available phosphorus to overcome the phosphorus constraint to plant growth in the Cape Flattery Sand.

The sand is dominated by medium and fine quartzitic grains; it contains a negligible portion of clay minerals which have reactive surfaces that are capable of chemical activity that is necessary for the sorption of phosphate. Hence, any small amount of phosphorus liberated from the Minplus™ by incubation or weathering in the soil will not be removed from the soil solution by the processes of phosphorus fixation. If the content of plant available phosphorus is very low in the soil, as it is in the Cape Flattery Sand, then the liberated phosphorus will be taken up by actively growing plants. Under such circumstances as prevail in the Cape Flattery Sand, there may be a subtle, but significant increase in plant growth that provides the clue to understanding an important process in Minplus™-amended soils.

### 5.4.5 Plant available silicon

A significant increase in available silicon was induced in the soils with the increasing application of Minplus<sup>TM</sup> treatments (Table 5.3). While silicon is not considered to be an essential element for plant growth (Salisbury and Ross, 1992), it may be important to certain plant species such as rice or sugarcane where silicon makes up an important component of the cell walls. Cereals and grasses normally contain 2 - 4 % SiO<sub>2</sub> in their vegetative parts, whereas dicotyledonous species commonly contain only 0.1 - 0.4 % (Jones and Handreck 1967).

## 5.5 Conclusions

A nutrient omission trial on the Cape Flattery Sand, which had received nil, low, and high rates of applications of Minplus<sup>TM</sup>, indicated that significant changes had been induced in the soil, including:

- enhanced supply of exchangeable basic cations, especially calcium,
  - dramatically reduced proportion of exchangeable acidic cation on the soil exchange complex,
  - increased soil pH (i.e. reduced soil acidity),
  - increased content of plant available phosphorus,
  - increased content of extractable silicon.
- 
- Minplus<sup>TM</sup> applications to the very sandy, strongly nutrient-deficient soil were found to be able to supply:
  - all the needs of the tomato plants for iron and sulphur ,
  - the bulk of the plant's needs for calcium, magnesium, and potassium,
  - a part of the plant's need for phosphorus,
  - none of the plant's need for nitrogen.

Minplus<sup>TM</sup> applications also produced significant changes in the chemical properties of the acidic, clay-rich Innisfail Clay and they are discussed in the following section (Chapter 6). In Chapter 7, the significance of the changes induced by Minplus<sup>TM</sup> is discussed in the context of results obtained from both the Cape Flattery Sand and Innisfail Clay, and the mechanisms whereby Minplus<sup>TM</sup> acts as an effective soil conditioner are explored.

## 6. Identifying constraints to plant growth: the Innisfail Clay

### 6.1 Research approach

The properties of the Innisfail Series Soil (Murtha 1986) have been outlined above (Section 4.2.1). Its acidic, clay-rich nature contrasts strongly with the that of the light textured Cape Flattery Sand of neutral soil pH. The Innisfail Clay presents constraints to plant growth and crop production that are typical of many of the heavier textured soils of the humid tropics.

In keeping with common soil survey practice, the name Innisfail Clay will be used henceforth in this report for the soil to reflect the texture of the surface layer of the soil (Soil Survey Staff 1951).

#### 6.1.1 Research questions

The three main research questions addressed by project activities on the Innisfail Clay and reported in this chapter are:

- What are the main nutritional deficiencies or other constraints to plant growth presented by the Innisfail Clay: calcium deficiency, magnesium deficiency, imbalances in the calcium : magnesium ratio, soil acidity, or phosphate fixation?
- Can Minplus™ applications overcome these constraints and, if so, to what extent?
- How does Minplus™ function in the soil to effect improvements in plant growth?

#### 6.1.2 Diagnosing plant growth disorders by nutrient addition trials

The nutrient addition approach relies on analysing the differential growth of an indicator plant to the supply of increasing amounts of an element of interest to the soil in which the plant is growing. Where the amount of the nutrient in the soil is inadequate to produce a full yield, growth will improve as the nutrient supply is increased (the 'Deficient zone' of Fig. 4.1). At higher levels of nutrient concentration, there is a yield plateau (the 'Adequate zone' of Fig. 4.1), and at even higher nutrient concentrations, growth may be inhibited by toxic levels of the nutrient.

It is a relatively simple approach, then, to set up a trial in which essential macronutrient elements, thought to be deficient in the soil, are supplied at increasing concentrations from a well chosen soil modifier. Similarly, by observing changes in growth of an indicator plant in response to the addition of increasing amounts of an alkaline soil modifier, the effect of reducing the acidity of the soil may be quantified.

The approach may be extended to soils to which increasing amounts of a soil conditioner such as Minplus™ have been applied in order to determine the contribution of the conditioner to the enhancement of plant growth in the amended soil.

The soil modifiers used in the nutrient addition trials reported below were chosen such that the 4 main effects of Minplus™ on highly weathered soils were addressed, namely calcium, magnesium, and phosphorus supplies to plants, and the effects of strong soil acidity on plant growth. They included:

- **a source of calcium:** calcium chloride,  $\text{CaCl}_2$ ,
- **a source of magnesium:** magnesium chloride,  $\text{MgCl}_2$ ,
- **a source of phosphorus:** disodium hydrogen orthophosphate,  $\text{Na}_2\text{HPO}_4$ ,
- **an agent to increase soil pH and reduce soil acidity:** calcium hydroxide,  $\text{Ca}(\text{OH})_2$ .

The first 2 soil modifiers were chosen in order to enrich the contents of the important basic cations in the soil and to address any possible deficiency or imbalance of calcium and magnesium. Chloride salts were chosen because they provided readily soluble forms of the basic cations in large enough amounts to allow a single application of the modifier, and the chloride anion causes no interference in the crucial soil reactions and plant growth responses at the concentrations used in the experiments.

A small pilot study was carried out in order to determine the more appropriate agent (calcium or sodium hydroxide) to neutralise soil acidity. Calcium hydroxide was found to react more quickly and had a higher neutralising value (Burton 1999), so it was chosen for the pot trial. In future studies, it is recommended that the sodium salt be used in order to avoid complications arising from the influence of calcium on plant growth in soils with low calcium contents or poor calcium : magnesium ratios.

The disodium hydrogen orthophosphate was used as a source of phosphorus, which was expected to be differentially sorbed in response to the various treatments imposed on the soil.

### 6.1.3 The experimental design

The nutrient addition pot trial on the Innisfail Clay consisted of:

$$3 \text{ Minplus}^{\text{TM}} \text{ application rates} \times 4 \text{ soil modifiers} \times 4 \text{ rates of application of soil modifiers} \times 5 \text{ replicates} = 240 \text{ pots}$$

To the 240 round, black plastic pots (9.2 cm diameter and 13.5 cm high) were added three sets of controls (using untreated, non-incubated Innisfail Clay), with 5 replicates in each set.

*Control CO (zero nutrient input):* One set of 5 replicates of untreated soil was watered using plain tap water.

*Control CL (low nutrient input):* A second set of replicates was watered with a full nutrient solution, containing all the required elements (Table 5.1) at 50% of the concentration outlined by Brownell (1979).

*Control CH (high nutrient input):* A third set of pots was watered with the nutrient solution at 150% of the concentration suggested by Brownell (1979). These plants received a “luxury level” of nutrients and should have, theoretically, shown the greatest biomass production.

The use of untreated soils and nutrient solution controls at three different concentrations x 5 replicates = 15 pots. Therefore, the total number of pots used = 240 + 15 = 255.

## 6.2 The Innisfail Clay

### 6.2.1 Study site and soils

The pot trial was established in a shadehouse of the School of Tropical Biology, James Cook University, Townsville, using a bulk supply of Innisfail Clay (Section 4.2.1). Approximately 1 t of soil was collected from a depth of 0-20 cm from the buffer zone between Blocks 1 and 2 of the experimental site at the Johnstone College of TAFE, Innisfail (Fig. 4.2).

### 6.2.2 Materials and methods

#### *Soil preparation*

The soil was transported to Townsville, air-dried at James Cook University, sieved to less than 2 mm, and mixed with Minplus<sup>TM</sup> in a clean, motorised cement mixer to produce the equivalents of application rates of 0, 2.5, and 25 t/ha (low, medium, and high rates respectively) in the pots.

Each of the bulk soil mixtures was incubated for 10 weeks following the procedure described above for the Cape Flattery Sand (Section 5.3.3).

The untreated soil was included for comparison of its properties with those of an untreated, non-incubated control in order to identify the effects, if any, of incubation. Unless otherwise indicated, all the 'controls' referred to below relate to the soil samples that had no Minplus™ additions, but had been incubated.

Immediately after incubation, the pots were filled with 780 g of clayey soil to ensure a uniform volume of soil in the pots for the plant roots to exploit. At this time, the incubated soil was at 100% field capacity and very difficult to manage. It is recommended that, in future experiments, the incubated soil be oven dried at 50 °C to halt the incubation reactions, and re-sieved to break up aggregates producing a more readily handled soil material.

#### *Indicator plant*

The tomato (*Lycopersicon esculentum* Mill., var. Grosse Lisse) was used as the indicator plant for the reasons set out above (Section 5.3.3).

A minimum of 4 tomato seeds was placed in each of the 255 pots on 13 May 1999 and loosely covered with soil. Some 6 – 10 days after planting, the seedlings were thinned to leave 1 per pot. Where all the seeds had failed to germinate in 4 of the pots, the thinned seedlings from replicates of the same treatment were transplanted.

The pots were placed at random on benches in the glasshouse (Fig. 5.1). Their locations were re-randomised each fortnight to reduce any possible effects of preferential exposure to light, air circulation, or other factors affecting growth.



**Figure 6.1** Part of the pot trial at James Cook University, Townsville, designed to use relative differences in growth of tomatoes as a bioassessment of the differences in samples of the Innisfail Clay that had been treated with 3 rates of Minplus™ and 4 rates of 4 soil modifiers. The experiment provided the basis for determining the nature of the constraints to plant growth presented by the soil, and the extent to which Minplus™ may overcome those constraints. The pots were arranged in treatment blocks for this photograph, which was taken about half way through the experiment.

#### *Nutrient and water regimes*

All the plants were given a basal dressing of a partial nutrient solution, which lacked the element used as a soil modifier in that particular component of the pot trial. (i.e. partial solutions lacking calcium, magnesium, or phosphorus, as appropriate). To ensure the attainment of **at least** minimal growth during the pot trial, the partial nutrient solutions were used at a concentration of 50% of that given by Tables 5.1 and 5.2. The soil moisture status was maintained at 80 – 100% of field capacity. Below this water content, the soil formed a surface seal and the small tomato indicator plants quickly wilted (in less than 4 hours), but they also recovered rapidly.

Even with the application to the CH controls of the partial nutrient solutions at 150% of the recommended concentrations of Tables 5.1 and 5.2, there were foliar symptoms of nutrient deficiencies. Darkening and

purpling of the older leaves of the tomato indicator plants, indicated a probable phosphorus deficiency (Barker 1989), and interveinal chlorosis may have been caused by a magnesium deficiency (Cresswell 1993). Because the fundamental aim of the experiment was to assess which nutrient deficiencies were present in the soil, and how Minplus™ may overcome them, the concentration of the basal nutrient solution had to be such that it did overcome the deficiencies by itself. Accordingly, a basal nutrient solution at 150% of that of Tables 5.1 and 5.2 was used which still allowed the indicator plants to provide an expression of the soil deficiencies.

#### *Application of soil modifiers*

Fourteen days after sowing the tomato seeds, the soil modifiers were watered into the soil as a one-off application. Immediately before applying the modifiers, the pots were watered to 80% of field capacity. The amounts of modifiers shown in Table 6.1 were dissolved in 20 mL of water per pot to provide the correct concentration of soil modifier at 100% field capacity, then watered into the pots. The 'low' value for each soil modifier was determined the minimum amount of the nutrient required to maintain plant growth in a nutrient culture solution (P.F. Brownell, pers. comm.). The 'medium' value was taken as twice the low value, and the 'high' value as four times the low value (Table 6.1). The high value for calcium hydroxide was determined by titration with the 'low' value taken as one quarter, and the 'medium' value at one half of the 'high' value (Burton 1999).

**Table 6.1** The amounts of soil modifiers dissolved in 20 mL of water and applied to each experimental pot (mg / pot) of Innisfail Clay are shown by the bold font. The resultant concentrations (mM) of soil modifiers in soil solution at a field capacity of 100% are also shown. Source: Burton (1999).

Soil modifier	Nil	Low		Medium		High	
		mg/pot	mM	mg/pot	mM	mg/pot	mM
Calcium chloride	<b>0</b>	<b>103.5</b>	4	<b>259.0</b>	10	<b>414.0</b>	16
Magnesium chloride	<b>0</b>	<b>22.2</b>	1	<b>55.5</b>	2.5	<b>88.8</b>	4
Calcium hydroxide	<b>0</b>	<b>15.4</b>	0.83	<b>38.4</b>	2.08	<b>61.4</b>	3.32
Disodium hydrogen orthophosphate	<b>0</b>	<b>66.2</b>	2	<b>165.0</b>	5	<b>265.0</b>	8

The general equation used to calculate the amount of the soil modifiers shown in Table 6.1 is:

$$A = (M \times FC \times MW / 1000) \text{ mL}$$

where:

- A = the amount of the soil modifier (g),
- M = the molarity of the modifying solution,
- FC = the amount of water held in the soil at field capacity,
- MW = the molecular weight of the soil modifier,

#### *Experimental measurements*

Measurements of plant growth, including plant height, numbers of expanded and expanding leaves, and length of the longest leaf, were made fortnightly and foliar symptoms of growth disorders such as interveinal chlorosis and purpling of the abaxial (underneath) side of the leaf were recorded. Munsell Plant Colour Charts were used to record the colours of leaf symptoms and a 5 unit rating system was developed (1 = virtually no purple on either side of leaf, to purple colours restricted to veins, purple colours in blotches on leaves, to 5 = deep purple colour over the whole of the leaf; Burton 1999).

On 18 July 1999 following 60 days of plant growth, the youngest fully mature leaf, the remaining shoots, and the roots were harvested separately. Soil was washed from the roots by gentle washing on a 2 mm sieve. All the plant materials were dried at 60°C, weighed to determine the total plant biomass produced by the relevant combination of Minplus™ treatment and soil modifier, and stored in preparation for chemical analysis.

As in the nutrient omission trial on the Cape Flattery Sand discussed in the previous chapter, fortnightly measurements of plant growth parameters were made, but ‘total plant biomass’ has been used as the best measurement that integrates the overall contribution of all the observed growth parameters.

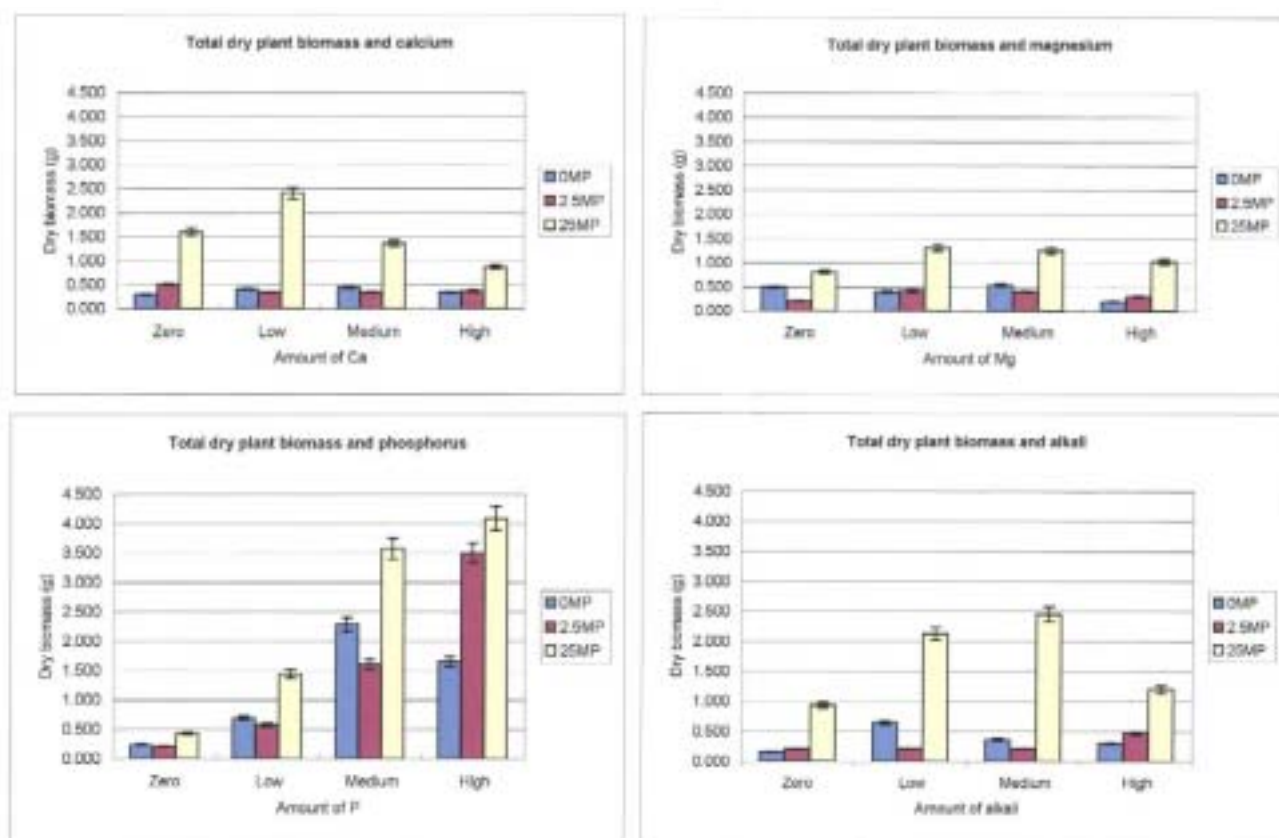
### Soil analyses

Immediately prior to harvest, the smallest, medium, and largest of the 5 plants that made up each replicated treatment were sampled for analysis. This reduced the number of samples for the analyses without reducing the variability inherent in the replicates. After collecting the plant shoots and before collecting the plant roots, the soils from the 3 pots were sampled using a hollow steel tube of 1.5 cm diameter, which was pushed to the bottom of the pot. Three cores were taken from each pot and their lengths recorded as a prelude to determining their bulk densities. The soil samples were air-dried, sieved to less than 2 mm, mixed, combined to provide a single sample from each of the 3 pots, weighed, and stored. All the soil chemical analyses followed the methods of Rayment and Higginson (1992).

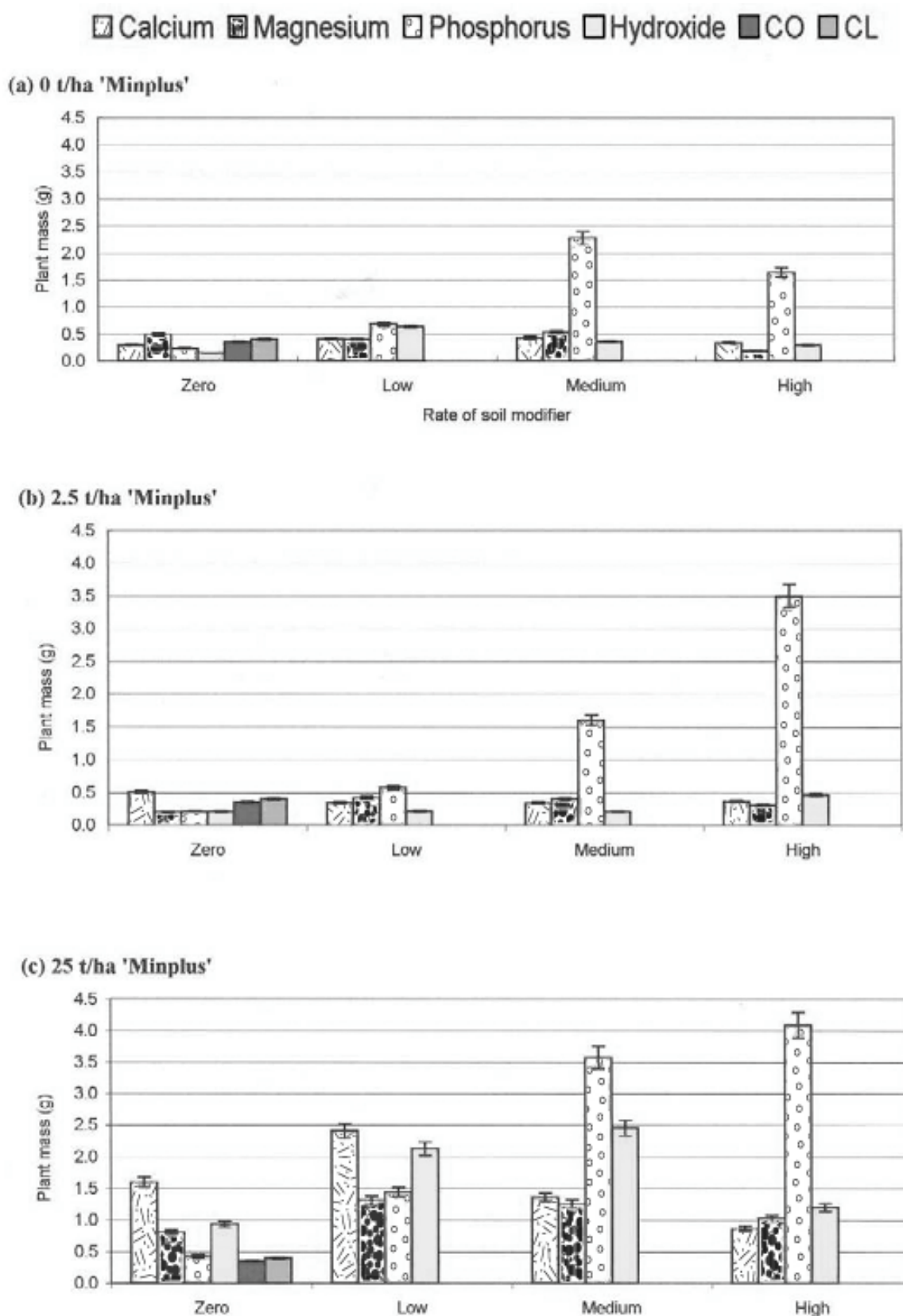
## 6.3 Plant growth responses to soil differences: results

### 6.3.1 Plant biomass production

Irrespective of the addition of any soil modifiers, there was a range of growth responses of the tomatoes to the Minplus™ treatments imposed on the Innisfail Clay (see ‘Zero soil modifier’ data of Figs 6.2 and 6.3). Similarly, dramatic growth differences became evident when the maximum amounts of soil modifiers were applied to soils with Nil and High Minplus™ treatments (compare Figs 6.4 and 6.5).



**Figure 6.2** Mean dry total plant biomass (shoots + roots; g) produced by tomato plants grown in the Innisfail Clay under different Minplus™ and soil modifier conditions. Minplus™ was applied at rates equivalent to 0, 2.5, and 25 t/ha. The amounts of soil modifiers applied as ‘low’, ‘medium’, and ‘high’ doses are given in Table 6.1. The biomass data represent the means of 5 replicates and the error bars indicate 95% confidence intervals. Source: Burton (1999).



**Figure 6.3** Mean dry total plant biomass (shoots + roots; g) produced by tomato plants grown in the Innisfail Clay under different Minplus™ and soil modifier conditions. Minplus™ was applied to the soil at rates equivalent to 0, 2.5, and 25 t/ha. The amounts of soil modifiers applied as 'low', 'medium', and 'high' doses are given in Table 6.1. The biomass data represent the means of 5 replicates and the error bars indicate 95% confidence intervals. Source: Burton (1999).





Figure 6.4. Growth responses at time of harvest of tomato plants grown in the Innisfail Clay with the *maximum amount of each soil modifier*, and *no Minplus<sup>TM</sup>* applied. Compare with the mean total dry biomass values of the 5 replicates in each treatment shown by the data for ‘High’ doses of soil modifiers in Fig. 6.3 a. The label on the pots indicates the order of soil modifier treatments (from the left): Low control, calcium, magnesium, phosphorus, and alkali.



Figure 6.5. Growth responses at time of harvest of tomato plants grown in the Innisfail Clay with the *maximum amount of each soil modifier*, and the *maximum amount of Minplus<sup>TM</sup>* applied (25 t/ha). Compare with the mean total dry biomass values of the 5 replicates in each treatment shown by the data for ‘High’ doses of soil modifiers in Fig. 6.3 c. The label on the pots indicates the order of soil modifier treatments (from the left): Low control, calcium, magnesium, phosphorus, and alkali.

Minimal differences in growth were evident between many of the zero and low (2.5 t/ha) Minplus™ treatments, but considerable growth increases at the highest rate (25 t/ha) of Minplus™ application (Fig. 6.2). Fairly uniform responses were produced by the calcium and magnesium treatments, with more dramatic responses from the alkali treatment. There was a very clear progressive increase in plant growth with increasing amounts of phosphorus added to the soil. Although a significant increase in growth was induced in the soils that had no Minplus™ additions, there was a highly significant growth increase in the soils to which the high dose rate of Minplus™ was applied (Fig. 6.2).

There were only slight, not statistically significant differences in plant growth induced in the two sets of control soils (see histogram columns 'CO' and 'CL' for 'Zero soil modifiers' of Fig. 6.3 a, b, c). Although some of the soil characteristics showed some slight differences as a result of the incubation process (Section 5.3.3, below), they had no significant effect on any constraints to plant growth.

### 6.3.2 Plant responses to Minplus™ and soil modifier treatments

The basal nutrient solution applied to all the pots ensured that the minimum amount of growth expected of the indicator plants would be that obtained in the treatment using the complete nutrient solution 'CL' (Brownell Solution; Table 5.1) at 50% concentration. Extremely poor growth of tomatoes in a number of the 'Zero' and 'Low' soil modifier treatments in the soils with nil or light Minplus™ applications (0 and 2.5 t/ha Minplus™) failed to attain the level of that in the CL control ('Zero soil modifiers' of Fig. 6.3 a, b). This suggests that, when the element of interest (Ca, Mg, or P) is lacking from the basal nutrient solution, there are inadequate supplies of that element in the soil to overcome the deficiency.

A summary of all the plant measurements taken at harvest is given in Table 6.2, and most of the measurements were highly significantly different ( $0.01 > p > 0.001$ , and  $p < 0.001$ ). In all cases, the effects of Minplus™ and the soil modifier produced statistically significant interactions.

**Table 6.2 Summary of analysis of variance results for the relationships between indicators of tomato plant growth and soil treatments. Source: Burton (1999).**

Plant parameter	Minplus™	Soil modifier	Interaction
Height 6 days after sowing	***	n.s.	***
Height at time of harvest	***	***	***
Length of longest leaf	***	***	**
Number of leaves	***	***	**
Total dry biomass at harvest (shoots + roots)	***	***	***
Dry root biomass : dry shoot biomass	***	***	***

n.s. (no significant effect); \* ( $0.05 > p > 0.01$ ); \*\* ( $0.01 > p > 0.001$ ); \*\*\* ( $p < 0.001$ )

#### *Zero Minplus™ treatments*

In the pots to which the soil modifiers but no Minplus™ had been added, there was little significant change in the plant biomass at all rates of soil modifier for the calcium, magnesium, and alkali treatments (Fig. 6.3 a). The dry biomass of phosphorus treated plants increased significantly at medium and high levels of phosphorus soil modifier (Fig. 6.3 a).

#### *Low (2.5 t/ha) Minplus™ treatments*

Plants treated with calcium, magnesium, and alkali soil modifiers and 2.5 t/ha Minplus™ showed little change in biomass at the increasing rates of soil modifier application (Fig. 6.3 b). Nor were there particularly strong differences in tomato growth in the calcium, magnesium, and alkali treatments applied at all 4 rates to the soils to which 0 and 2.5 t/ha of Minplus™ had been applied. The phosphorus treatments produced strong growth

differences, particularly at 'Medium' and 'High' levels of phosphorus (Fig. 6.2). The total plant biomass was significantly much greater than that produced by all the other treatments in the soils to which 0 and 2.5 t/ha of Minplus<sup>TM</sup> had been applied (Fig. 6.3 a, b).

#### *High (25 t/ha) Minplus<sup>TM</sup> treatments*

From the time of germination, and before the addition of any soil modifiers, most of the plants treated with high levels of Minplus<sup>TM</sup> appeared to be stronger, producing their first set of leaves at a time when tomato seedlings in other treatments were still emerging. Those treated with high rates of Minplus<sup>TM</sup> and phosphorus showed much less intense foliar symptoms of nutrient deficiency at juvenile growth stages, and no such symptoms at harvest.

Plants in the calcium, magnesium and hydroxide treatments all produced more biomass overall than they had in the 0 t/ha and 2.5 t/ha treatments (Fig. 6.3 c), however, at medium and high rates of soil modifier application, the growth in the calcium treatments progressively decreased.

Biomass production in the magnesium treatments showed a similar, but not as pronounced trend to that of the calcium treatments (Fig. 6.3 c). Indicator plants treated with the alkali source (calcium hydroxide) followed a similar pattern to the calcium treatments, but growth was considerably higher than that produced by the use of calcium chloride as a soil modifier (Fig. 6.3 c).

#### *Foliar symptoms of nutrient deficiencies*

The control plants receiving water only showed the strongest level of leaf discolouration (purple colour graded 5 = worst; Section 6.2.1, above), while those watered with the 50% nutrient solution showed up to 2 grades improvement (graded 3 = medium).

Plants treated with higher rates of Minplus<sup>TM</sup>, phosphorus, or alkali soil modifiers generally appeared to have less purpling on the abaxial side of the older leaves (purple colour generally graded 2 to 3). No chlorosis, curling, or necrosis of leaves was observed on any plant, though, many plants in the calcium and magnesium treatments appeared to be stunted in growth.

#### *Root : shoot ratios*

Many of the root masses in the 0 and 2.5 t/ha Minplus<sup>TM</sup> treatments were too small to detect any of the symptoms which have been reported in root systems affected by high levels of aluminium (Grundon *et al.* 1987 and 1997). All the roots in the high Minplus<sup>TM</sup> treatments appeared to be healthy.

If the soil nutrients are abundant, especially phosphorus (Pilbeam *et al.* 1993), root : shoot ratios are generally small; when the soil nutrient contents are low, this ratio increases as the plant allocates more resources to the root system in an attempt to exploit a larger surface area from which to absorb nutrients (Moorby and Besford 1983). Similarly, Baylis *et al.* (1994) have demonstrated the severe reduction of root mass that is a consequence of growth in acidic soils with high concentrations of exchangeable aluminium in the soil solution.

The root : shoot ratios for the controls were 1.79 (zero control = plain water), 0.59 (low control = 50% Brownell solution; Table 5.1), and 0.4 (high control = 100% Brownell solution; Table 5.1). Hence, the root mass decreased as the contents of available nutrients increased. The root: shoot ratios also decreased (from 1.99, to 1.78, and 0.38) with increasing Minplus<sup>TM</sup> applications, indicating that greater levels of nutrients were being made available to the plants at the heavier application rates (Moorby and Besford 1983). The plants are also responding to parallel and highly significant decreases in the proportion of acidic cations on the exchange complex of the soil (Table 6.4), which also encourages root growth (Bayliss *et al.* 1994).

### **6.3.3 Soil responses to Minplus<sup>TM</sup> and soil modifier treatments**

The differences in the soil properties of greatest interest in this study are summarised in Table 6.3, with data from the baseline samples from the field trial at the Johnstone College of TAFE (Section 4.2.1, above) and the low control (CL) values which were at the same concentration of nutrient solution received by all treatments in the pot trial.

### *Effects of incubation*

The soil chemical properties of the baseline (unincubated soil) samples, and those from the low control ('CL', unincubated soil and 50% Brownell solution; Table 5.1) used in the pot trial, were similar in most aspects to those of the 'Nil Minplus<sup>TM</sup>' treatment (Table 6.3).

Incubating the untreated soil produced some slight differences in soil chemical properties. These differences are evident from comparisons between the data in Table 6.3 for the 'baseline samples' (non-incubated soil from the field trial) and the untreated soils that had been incubated for 10 weeks in the presence of water alone (the 'Nil Minplus<sup>TM</sup>' samples). The slightly higher content of exchangeable basic cations in the Nil Minplus<sup>TM</sup> samples was matched by a similarly lower content of exchangeable acidic cations, to produce no significant difference in ECEC of both sets of samples (Table 6.3). Incubation also produced slightly elevated soil pH and plant available phosphorus contents (Table 6.3).

These differences are not entirely consistent with those caused by incubation on soil chemical properties and identified by Brown (1999), including: decreased soil pH, increased extractable phosphorus, exchangeable aluminium and electrical conductivity, and variable changes in exchangeable calcium, magnesium, and sodium.

### *Effects of Minplus<sup>TM</sup> applications*

There were no significant differences in all the soil properties listed in Table 6.3 for the 'Nil Minplus<sup>TM</sup>' and 'Low Minplus<sup>TM</sup>' soils. They were all significantly different ( $p < 0.05$ , and often  $p < 0.001$ ) from the soils amended with high application rates of Minplus<sup>TM</sup> (Table 6.3).

The 'High Minplus<sup>TM</sup>' treatment produced a strong increase in basic cations, particularly in magnesium and sodium, and an important decrease in acidic cations, resulting in a significant increase in ECEC over that of all the other treatments (Table 6.3). The increase in exchangeable magnesium levels produced a significant decline in the calcium : magnesium ratio (Table 6.3) at the 'Low' and 'High' rates of Minplus<sup>TM</sup> application. Despite increases in the exchangeable sodium in the soil, the electrical conductivity in those treatments decreased (Table 6.3).

**Table 6.3** Selected mean chemical properties of the Innisfail Clay samples from different treatments in both the field and pot trials. Source: Burton (1999).

Soil property	Baseline <sup>+</sup> (Untreated field samples)	Low control <sup>++</sup> (‘CL’, 50% nutrient solution)	Minplus <sup>TM</sup> application rates		
			Nil 0 t/ha	Low 2.5 t/ha	High 25 t/ha
pH <sub>water</sub>	4.6 c	4.59 c	4.72 b	4.82 b	5.4 a
Exchangeable Ca (cmol/kg)	2.2 c	2.9 b	3.0 b	2.9 b	3.3 a
Exchangeable Mg (cmol/kg)	1.2 b	1.1 c	1.0 c	1.4 b	3.2 a
Exchangeable K (cmol/kg)	0.4 a	0.4 a	0.3 a	0.4 a	0.3 a
Exchangeable Na (cmol/kg)	0.1 a	0.2 a	0.5 b	0.5 b	0.7 b
Total basic cations (cmol/kg)	3.91 d	4.56 c	4.72 c	5.02 b	7.58 a
Total acidic cations (cmol/kg)	1.2 a	1.02b	0.93 c	0.77 c	0.18 d
ECEC (cmol/kg)	5.11 b	5.57 b	5.65 b	5.79 b	7.67 a
Calcium : magnesium ratio	1.8	2.6	2.9	2.1	1.1
Plant available phosphorus (mg/kg)	35 c	44 b	41 b	40 b	48 a
Electrical conductivity ( S / cm)	n.d.	158.2 a	271.4 c	238.1 c	205.7 b

Means followed by the same letter across a row are not significantly different.

<sup>+</sup> Baseline samples were collected from field site before the establishment of the field trial and the application of any soil conditioners or fertiliser.

<sup>++</sup> Low control (CL): unincubated soil and Brownell nutrient solution at 50% concentration (Table 5.1)

The soil pH and plant available phosphorus contents increased to levels which are more able to sustain plant growth (ideally, soil pH 5.5 - 7; plant available phosphorus contents 6 - 300 ppm, Cumming and Elliott 1991). A similar, though much less dramatic trend occurred in soils treated with the low application rate of Minplus<sup>TM</sup>, with respect to the untreated soils (compare data for ‘Low Minplus<sup>TM</sup>, 2.5 t/ha’ samples with those for the ‘Baseline’ samples; Table 6.3).

The proportions of the cations in the cation exchange complex of the soil were altered considerably by both Minplus<sup>TM</sup> application rates. Although the soils of the low control had a similar ECEC to the ‘Nil Minplus<sup>TM</sup>’ and ‘Low Minplus<sup>TM</sup>’ treatments, they had a higher percentage of acidic cations (Table 6.4), which indicates greater reserve acidity.

**Table 6.4** Soil cation contents of differently treated samples of the Innisfail Clay expressed as a percentage of the effective cation exchange capacity (ECEC). Source: Burton (1999).

Cation	Baseline <sup>+</sup> (Untreated field samples)	Low control <sup>++</sup> (‘CL’, 50% nutrient solution)	Minplus <sup>TM</sup> application rates		
			Nil 0 t/ha	Low 2.5 t/ha	High 25 t/ha
Calcium	41	52	53	50	43
Magnesium	24	20	18	24	41
Potassium	7	7	6	5	4
Sodium	2	3	7	8	9
Hydrogen and aluminium	26	18	16	13	2

<sup>+</sup> Baseline samples were collected from field site before the establishment of the field trial and the application of any soil conditioners or fertiliser.

<sup>++</sup> Low control (CL): unincubated soil and 50% Brownell solution (Table 5.1)

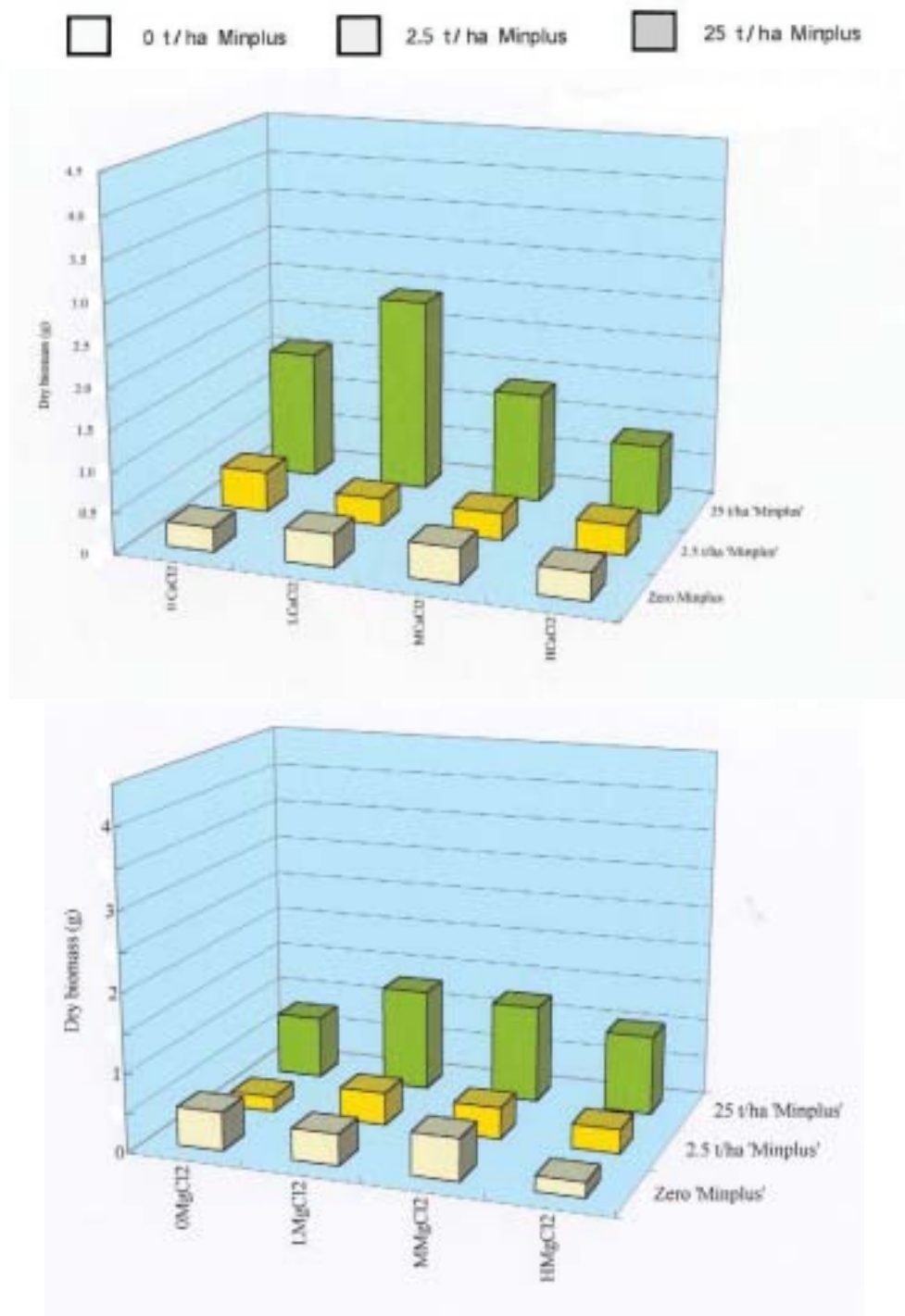
## 6.4 Summary of results

The significant changes seen in several soil properties (exchangeable potassium, exchangeable sodium, and electrical conductivity) appear to be caused by the soil modifiers and Minplus<sup>TM</sup> acting independently on the soil (Table 6.5). Other significant differences in the other soil chemical properties suggest that both Minplus<sup>TM</sup> and the soil modifier had significant effects, and more importantly, they acted together to achieve those effects (Table 6.5).

**Table 6.5** Summary of analysis of variance results of relationships between soil chemical properties of the Innisfail Clay and soil treatments. Source: Burton (1999).

Soil parameter	Minplus <sup>TM</sup>	Soil modifier	Interaction
Exchangeable Ca	***	n.s.	*
Exchangeable Mg	***	***	***
Exchangeable K	**	***	n.s.
Exchangeable Na	***	***	n.s.
Exchangeable H + Al	***	***	**
Effective CEC	***	***	**
Available P	***	***	***
pH	***	***	***
Electrical conductivity	**	***	n.s.

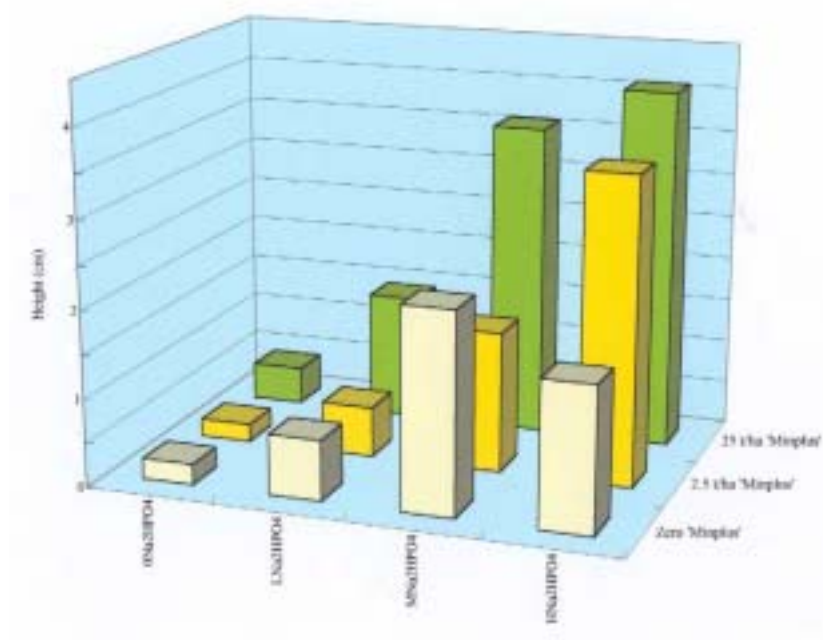
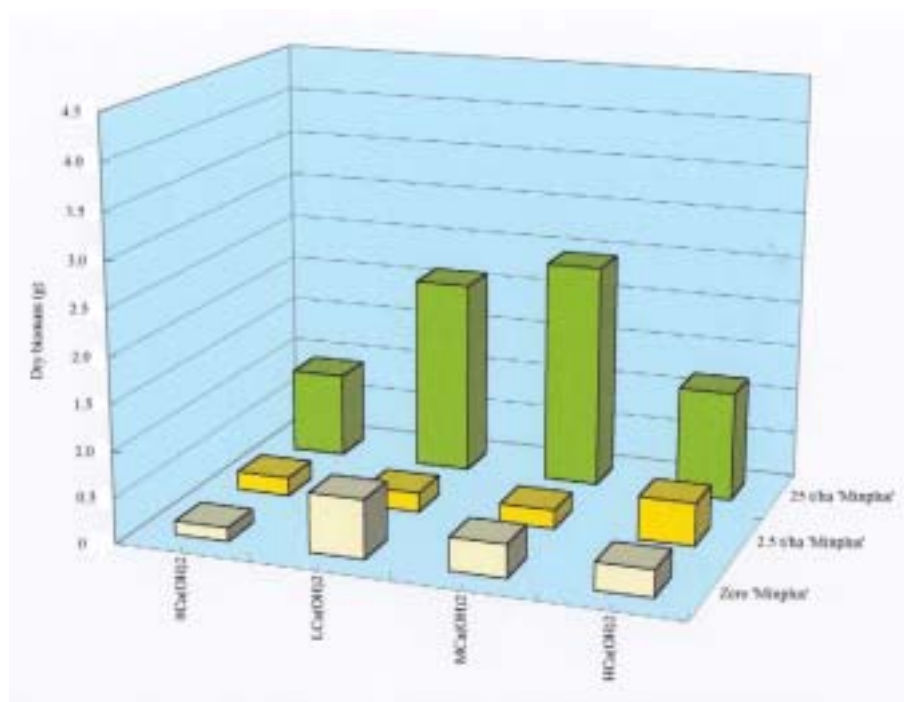
n.s. (no significant effect); \* (0.05 > p > 0.01); \*\* (0.01 > p > 0.001); \*\*\* (p < 0.001)



Figures 6.6 a and b. Mean dry total biomass (shoots + roots) of tomato plants grown in pots of the Innisfail Clay under different combinations of applications of Minplus<sup>TM</sup> and calcium and magnesium soil modifiers.  $n = 5$  for each column. The significance of the differences in plant growth responses is shown graphically in Figs 6.2 and 6.3. Source: Burton (1999).

Symbols used:

0, L, M, H  $\text{CaCl}_2$  and 0, L, M, H  $\text{MgCl}_2$  = Nil, Low, Medium, and High application rates of calcium chloride or magnesium chloride soil modifier, respectively (see Table 6.1). The 'Nil Minplus<sup>TM</sup>' treatments are represented by the pale-coloured front row of columns, 2.5 t/ha Minplus<sup>TM</sup> by the middle row, and 25 t/ha Minplus<sup>TM</sup> by the taller back row of columns.



Figures 6.6 c and d. Mean dry total biomass (shoots + roots) of tomato plants grown in pots of the Innisfail Clay under different combinations of applications of Minplus™ and alkali and phosphorus soil modifiers.  $n = 5$  for each column. The significance of the differences in plant growth responses is shown graphically in Figs 6.2 and 6.3. Source: Burton (1999).

Symbols used:

0, L, M, H  $\text{Ca(OH)}_2$  and 0, L, M, H  $\text{Na}_2\text{HPO}_4$  = Nil, Low, Medium, and High application rates of calcium hydroxide or disodium hydrogen orthophosphate soil modifier, respectively (see Table 6.1). Nil Minplus™ is represented by the pale-coloured front row of columns, 2.5 t/ha Minplus™ by the middle row, and 25 t/ha Minplus™ by the taller back row of columns.



The growth responses of the tomato indicator plants to the 3 application rates of Minplus<sup>TM</sup> and the 4 rates of application of the 4 soil modifiers have been analysed in the previous section. The data for the 3 variables (growth response, Minplus<sup>TM</sup>, and soil modifiers) are brought together in a three dimensional diagrams in Fig. 6.6. Clearly, the strongest growth responses have been produced by the addition of phosphorus to the Minplus<sup>TM</sup>-treated soils (Fig 6.6 d). Except for the marked response to added phosphorus, there was very little difference across all the treatments in plant growth responses to no Minplus<sup>TM</sup> and the light dressing of 2.5 t/ha (Fig. 6.6).

Results from the present study have shown that the Innisfail Series soil has adequate levels of basic cations to support plant growth, an excess of acidic cations, and a deficiency in available phosphorus (Table 6.3). The relatively high level of acidic cations is a response to the high reserve acidity of the soil, which controls its active acidity creating a low soil pH, further inhibiting the plant availability of the low phosphorus supply (Bruce 1988). Contents of exchangeable sodium are relatively low, and the electrical conductivities of the Minplus<sup>TM</sup>-treated soils all lie below of 3000 S / cm, which is thought to be the threshold above which there are noteworthy effects on plant growth (Handreck and Black 1994).

## 7. Overcoming constraints to plant growth in highly weathered soils

### 7.1 Nature of highly weathered soils

Highly weathered soils occur in the tropics and are commonly found on land surfaces that have undergone extensive leaching as a consequence of their age, climatic setting, or both. The high temperatures and rainfall promote intensive weathering and leaching processes in the soils, whose capacity to sustain plant growth has been reduced by a number of processes, including:

- rapid oxidation and loss of soil organic matter, despite the high rainfall and temperatures promoting rapid growth of vegetation and the production of large volumes of organic debris on the soil surface;
- breakdown of inorganic minerals in the parent rocks from which the soils have formed;
- leaching of many of the readily soluble, essential plant nutrients derived from the soil organic matter and weathering soil parent materials, especially nitrogen and phosphorus;
- loss of net negative charge on the surfaces of soil colloids and the development of low capacity for the soil to retain cations and supply them to growing plants (i.e. the development of low cation exchange capacity in the soil),
- severe depletion of reserves of basic cations in the soil, especially of calcium, magnesium, and potassium;
- concentration of acidic cations, aluminium and hydrogen, resulting in the development of acidic to very strongly acidic conditions (i.e. low soil pH) in the rootzones of plants;
- loss from the soil profile of soluble silicon, which is not essential to support plant growth, but whose absence from the soil may severely diminish the productivity of a number of crops in the humid tropic;
- accumulation in the soil profile of relatively immobile elements such as iron and aluminium oxides and oxyhydroxides;
- enhanced capacity of the soil to fix phosphorus creating very low availability and strong plant requirements for supplements of this element from phosphatic fertilisers.

The pH of a soil exerts a major control over the retention of nutrient ions on the surfaces of soil colloids or in the soil solution and their uptake by plants. At the low pH values commonly encountered in highly weathered soils (soil pH less than 5.5), the cation exchange complex of the soil becomes increasingly dominated by aluminium and hydrogen, and many nutrients become unavailable to plants.

Land managers seek to rectify the low availability of nutrients by adding soil amendments such as fertilisers, or by increasing soil pH with lime. Liming is uneconomic in many situations due to the amounts needed to overcome the strong active acidity of the soil, and the high reserve acidity effects of aluminium and iron oxides in the clay fraction of highly weathered soil systems. Heavy applications of lime will flood the exchange complex of the soil with calcium ions to the detriment of the other basic cations; calcium : magnesium imbalances often result in the soil (Tisdale *et al.* 1993, p. 298). Liming also produces large amounts of carbon dioxide which, when liberated into the atmosphere as a consequence of neutralising soil acidity, contributes to the global greenhouse gas problem (see Section 3.2.3, above).

The effect of mineralogy of several weathered tropical soils on their lime requirement was investigated by Gillman and Sumpter (1986), who reported that soils from granitic and metamorphic parent materials need lime equivalent to the exchangeable aluminium content; whereas soils from basaltic parent materials require much more lime, equivalent to 2 to 3 times that of the amount of exchangeable aluminium in the soil solution. The limitations of traditional liming materials due to their short effective life spans in tropical regions of high rainfall has prompted research into the use of silicate-based soil conditioners such as crushed basalt to sustain agricultural production in the humid tropical regions of the world.

This chapter addresses the results of some of that research in north Queensland. In summary, the present project has demonstrated the ability of Minplus™, a basaltic rock dust, to provide essential nutrients to the soil, and to overcome chemical deficiencies that occur to varying extents in a variety of soils. Minplus™ can reduce the growth-inhibiting effects of soil acidity, and can alleviate the strong phosphorus fixing capacity of many highly weathered soils. Some of the ways in which Minplus™ achieves these dramatic changes as a conditioner of the properties of highly weathered soils are discussed below.

## 7.2 Minplus™ applications and exchange properties of soils

The Cape Flattery Sand has a very low colloid content and an extremely low cation exchange capacity. The soil displayed a total ECEC of only 0.31 cmol/kg and, of this, exchangeable calcium contributed some 0.08 cmolc / kg (Table 5.3). In terms of the criteria of Reghenzani (1987) and Hailes *et al.* (1997), the soil is extremely deficient in all the basic cations, which is evident in its classical plant growth responses to any of the cations added to the soil from either Minplus™ applications or nutrient solutions (Figs 5.1 a, b and 5.2).

Therefore, the cation chemistry of the Cape Flattery Sand is not considered further in this section; the reported results are derived from our experiments on the Innisfail Clay.

### 7.2.1 Calcium

The average value for exchangeable calcium from 91 acid soils in Queensland was found by Bruce (1999) to be 2.4 cmol/kg, with a range of 0.17 – 14 cmol/kg. Calcium deficiency in north Queensland soils is known to occur when the exchangeable calcium content is less than 1.5 cmol/kg, and that the best responses to calcium applications are achieved only if the exchangeable calcium levels are less than 0.65 cmol/kg. (Reghenzani 1987).

The Innisfail Clay (exchangeable calcium = 2.2 cmol/kg; Table 4.1) could be considered to lie in the middle to lower end of the acceptable range, but not truly deficient. Although the amount of exchangeable calcium in the soil was increased by both rates of Minplus™ application, it was not increased by the same proportion as was the exchangeable magnesium content (Table 6.4), even though the elements are supplied by Minplus™ in almost equal amounts.

The consistently poor growth responses of the plants grown in the Innisfail Clay with no Minplus™ and treated with increasing amounts of the calcium soil modifier have shown that the soil is not calcium deficient (Figs 6.2 and 7.1). Higher contents of trace elements or plant available phosphorus derived from the basaltic rock dust, or improved soil physical properties, may possibly have caused the increased growth at high rates of Minplus™.



**Figure 7.1** Stunted growth of tomatoes grown in the Innisfail Clay for 60 days with (from left to right) increasing amounts of calcium chloride soil modifier applied, but no Minplus<sup>TM</sup> amendment.



**Figure 7.2** Stunted growth of tomatoes grown in the Innisfail Clay for 60 days with (from left to right) increasing amounts of magnesium chloride soil modifier applied, but no Minplus<sup>TM</sup> amendment.

The decline in plant growth at high rates of application of both the calcium soil modifier and Minplus™ to the Innisfail Clay (Figs 6.4, 6.6, and 7.1) was initially interpreted as evidence of a possible calcium toxicity. Marschner (1983) found the relative growth rate of tomatoes decreased when the supply of calcium in the nutrient solution increased from 100 to 1000 M; the range of exchangeable calcium in the soils of the pot trial was 4000 M to 13,600 M (Burton 1999). While some of the stunting of plants observed in these treatments may be due to excess calcium (Handreck and Black 1994), there were no other signs of nutrient toxicity such as lesions on the leaves (Cresswell 1993). The actual level of exchangeable calcium was increased by less than 1 cmol/kg in the soil (Table 6.3), so the stunted growth was not considered to be a sign of calcium toxicity alone. Other factors are involved and are discussed below.

## 7.2.2 Magnesium

Despite historic reports that Australian soils are not magnesium deficient (Aitken and Scott 1999), Hailes *et al.* (1997) considered such reports to be misleading because the data were from temperate regions of Australia. Many northern soils have low magnesium contents and Hailes *et al.* (1997) reported that only exchangeable magnesium values less than 0.3 cmol/kg should be considered deficient. The range quoted by Hailes *et al.* (1997) for exchangeable magnesium in tropical soils was 0.02 - 13.45 cmol/kg, with a mean of 1.10 cmol/kg.

The Innisfail Clay, with an exchangeable magnesium content of 1.23 cmol/kg (Table 4.1) could be considered higher than average, but near the lower end of the adequate range of Hailes *et al.* (1997).

As the actual content of exchangeable magnesium in the soil may vary spatially, the percentage of magnesium in the exchange complex was thought by Conyers (1999), to be a better guide. The optimal magnesium saturation was defined as 6 – 10% (Metson 1974), with deficient soils having magnesium saturation values less than 6% (Hailes *et al.* 1997). As exchangeable magnesium constitutes 18 – 24% of the exchange capacity of the Innisfail Clay (Table 6.4), it is not considered that the soil is magnesium deficient by this definition.

Though the most prominent improvement in the basic cations in the Minplus™-treated soil was seen in its exchangeable magnesium content, this element made no contribution to increased plant growth. The magnesium treatments were consistent in their lack of growth responses across all rates of Minplus™ application (Figs 6.2 and 6.3), with very little change at increasing rates of this soil modifier (Fig. 6.6 b), also indicating that there is no magnesium deficiency in the Innisfail Clay.

## 7.2.3 Calcium : magnesium ratio

While the levels of exchangeable calcium and magnesium in the soil are important to plant growth, the balance between the two elements may be even more important (Macleod *et al.* 1984). Simson *et al.* (1979) studied reports of nutrient imbalances in soils following liming with dolomite, and found that the evidence for Mg toxicity was highly variable. In addition, in soils with low calcium : magnesium ratios, plant yields could be limited by calcium deficiency, magnesium toxicity, or simply by an imbalance between the two elements (Simson *et al.* 1979). More recently, Aitken and Scott (1999) attributed a decline in citrus growth to an oversupply, in the exchange complex of the soil, of magnesium in relation to calcium.

There is still considerable discussion about the nature of an ideal calcium : magnesium ratio in soils for plant growth, but there seems to be some agreement that if the ratio is less than 1.0, there may be nutrient supply problems (Conyers 1999).

The plants grown in the untreated Innisfail Clay treated with high application rates of the calcium, magnesium, and alkali soil modifiers were stunted, rarely exceeding the growth of the controls to which no soil modifier was added (Figs 6.6 a, b, c and 7.2). They may have experienced a magnesium toxicity, which rarely occurs in soils (Handreck and Black 1994), or a calcium : magnesium ratio imbalance which affected growth at the high rates of application of the soil modifiers. The balance of calcium and magnesium in the total cation exchange complex of a soil required to ensure near-optimal growth of plants is considered to be 60 – 80% calcium and 10 – 15% magnesium (Handreck and Black 1994). The exchangeable calcium and magnesium contents in the Innisfail Clay treated with the high application rate of Minplus™ (Table 6.4) were 43% and 41% of the total exchange capacity respectively, producing a calcium : magnesium ratio of 1.05.

Hence, it is thought that an imbalance in the calcium : magnesium ratio has seriously inhibited plant growth in some of the high Minplus™ treatments in the pot trial, especially those involving the addition of extra calcium as calcium chloride or as the alkali, calcium hydroxide (Fig. 6.3).

There have been reports that increased magnesium levels may lead to improved phosphorus metabolism in plants (Glendinning 1999), which may account for some of the sustained good growth in the phosphorus treatments of the Innisfail Clay with high Minplus™ (Figs 6.5 and 6.6 d) despite the associated low calcium : magnesium ratio.

#### 7.2.4 Potassium and sodium

Despite Minplus™ containing 1.7% of K<sub>2</sub>O (Table 2.1), and some 4 – 5 me of exchangeable potassium being available per 100 g of rock dust (Fig. 2.2 c), the levels of exchangeable potassium were hardly altered in any of the Minplus™ treatments (Tables 6.3 and 6.4).

Minplus™ did increase the level of exchangeable sodium in the soil in some of the treatments (Tables 6.3 and 6.4), but not to levels which are thought would affect plant growth (greater than 300 S / cm; Cumming and Elliott 1991).

With the increasing application rates of Minplus™ and the associated increasing amounts of exchangeable sodium in the amended soils, the electrical conductivity of the soils actually decreased (Table 6.3). This may be because the exchangeable sodium forms only a small part of the electrical charge on the colloid surfaces of the Innisfail Clay, so increases in its availability in the soil are not necessarily reflected in the electrical conductivity of the soil.

#### 7.2.5 Cations and leaching

The ECEC of the baseline soil samples was 5.11 cmol/kg (Table 4.1) and well above the 4 me /100 g that is described as the ‘minimum required to minimise the loss of cations through leaching’ (Sanchez 1976). Hence, the addition of even low rates of Minplus™ should raise the ECEC sufficiently to further reduce the possibility of loss of cations through leaching. The laboratory leaching experiment that simulated the application of a year’s rainfall on a group of humid tropical soils treated with varying rates of Minplus™ (Chapter 8, below) showed that the overall retention rate of added cations was approximately 75%. Hence, much of the improvement in the cation exchange capacity of Minplus™-treated soils might be maintained in the field from one season to the next.

### 7.3 Minplus™ applications and soil acidity

Profiles of the Innisfail Clay are strongly acidic (Murtha 1986) which has been confirmed by the present study (Table 6.3). In such soils, the proportion of aluminium cations in the exchange complex may achieve toxic levels (Sections 1.2.2 and 3.2, above). The proportion of exchangeable aluminium in the ECEC can be used as an indicator of possible aluminium toxicity, but the proportion that is toxic to plants depends on the plant species and soil type. For example, the growth of lucerne (*Medicago sativa*), a legume, may be affected if aluminium constitutes more than 1% of the ECEC, but *Stylosanthes guianensis*, another legume, may tolerate exchangeable aluminium levels of 40% of the total cations in grey podzolic soils (Conyers 1999).

It is difficult, however, to find in the soils literature an ‘ideal value’ for the content of acidic cations in the soil. Nevertheless, because the acidic cation content of the exchange complex governs both the reserve and active acidity of the soil (Glendinning 1999), it is preferable to reduce the proportion of acidic cations to the lowest level possible.

There were marked reductions in the amount and proportion of acidic cations in the range of soils amended with increasing Minplus™ applications, with the effect evident even in the low Minplus™ treatments (Tables 6.3 and 6.4). The important consequence of the declining proportions of acidic cations in the soils was the commensurate improvement in plant growth (Figs 6.2 and 6.6 c), and a reduction in nutrient deficiency symptoms in the plant leaves (Section 6.3.2).

Therefore, it is considered that soil acidity is a major constraint to plant growth, which can be overcome or significantly reduced in the Innisfail Clay and other soils (Section 3.2.4) by using Minplus™ at application rates higher than 2.5 t/ha, but not necessarily as high as 25 t/ha.

The pH of the Cape Flattery Sand ranged from 6.64 in its untreated state to 6.91 under the High application rate of Minplus™ (Table 5.3). In either its natural or amended state, the soil is at a pH which is likely to produce near-optimal plant growth (Fig. 3.2).

### 7.3.1 Liming acidic soils

Lime products, like calcium carbonate or calcium hydroxide, are used to supply calcium, which will result in the reduction of the levels of exchangeable and soluble aluminium in the soil (Reghenzani 1987). Hence, the reduction in the proportion of acidic cations in the exchange complexes of soils amended with high Minplus™ application rates could be due to an increased calcium supply. The application of increasing amounts of calcium as calcium chloride, however, did not improve plant growth in the pot trial (Fig. 6.2 a). Indeed, it appeared to hinder growth slightly and the content of exchangeable calcium in the soil did not increase appreciably (Table 6.3). In the untreated baseline soil samples collected from the field site at the Johnstone College of TAFE, Innisfail, prior to establishing the field trial, 41% of the ECEC consisted of exchangeable calcium, and 26% was acidic cations (Table 6.4). With the application of the high rate of Minplus™, the percentage of calcium on the exchange complex had changed little (43%), but the percentage of exchangeable acidic cations had been dramatically reduced to less than 3% (Table 6.4).

Clearly, it is not calcium that is responsible for this massive reduction in the content of acidic cations induced by the Minplus™ application to the soil. Other factors are involved and are discussed below.

## 7.4 Minplus™ applications and soil phosphorus

### *Innisfail Clay*

Phosphorus supply is thought to be a factor limiting plant growth in many humid tropical soils (Bowden et al. 1980). The Innisfail Clay has a very high phosphorus fixing capacity (Section 3.6.2, above). Plant growth response to applications of phosphorus to untreated soils is poor to mediocre (Figs 6.2 c and Fig. 7.3). Soil analyses indicate that the untreated soils have significantly lower contents of plant available phosphorus than the soils that have been amended with the high rates of Minplus™ (Table 6.3). The higher contents of plant available phosphorus are reflected in the substantially better plant growth in the High Minplus™ treatments (Figs 6.2 c, 6.6 d, and 7.4). Plants growing in soils lacking adequate levels of phosphorus are unable to convert sugar into cellulose and starch, resulting in a build up of sugars and the formation of anthocyanins, which will be evident in the plant as a purple discolouration on the abaxial side of the older leaves (Troeh and Thompson 1993). While such discolouration can occur with injury, temperature damage (Troeh and Thompson 1993), and very severe nitrogen deficiency (Cresswell 1993), these factors had no influence in the present study. Thus, the marked discolouration on the abaxial side of the tomato leaves was thought to be a consequence of a soil phosphorus deficiency, which was relieved to various degrees by the Minplus™, phosphorus, and alkali treatments. The greatest levels of plant available phosphorus in the soil were found in the phosphorus and alkali treatments, which coincided with the lower levels of leaf discolouration (Section 6.3.2, above).

Plant biomasses in the treatments with no added phosphorus were extremely low across the range of Minplus™ amendment rates ('Zero amount of P' data; Fig. 6.2 c). Therefore, it appears that either Minplus™ alone cannot supply sufficient available phosphorus to improve plant growth without the addition of supplementary phosphorus, or that the amounts of phosphorus, which were supplied by the treatments, were quickly adsorbed by the soil colloids. The plant growth response to the low Minplus™ application rate was less than the response to the high rate at all added phosphorus levels (Figs 6.2 and 6.6 d). The slow rates of leaching of Minplus™ from the soil (Section 3.7, above) suggest that the bulk of any Minplus™ addition is likely to remain in the soil, providing a long-term, albeit small, source of phosphorus.



**Figure 7.3** Responses of tomatoes grown for 60 days in the Innisfail Clay treated with different amounts of Minplus<sup>TM</sup> soil conditioner and different levels of phosphorus supplementation.

The plant on the left received no Minplus<sup>TM</sup> and no phosphorus (its basal nutrient solution lacked phosphorus); the control (centre) received no Minplus<sup>TM</sup> and phosphorus in the basal nutrient solution (50% concentration; Table 5.1); the plant on the right received a high application rate of Minplus<sup>TM</sup> (25 t/ha) and a high rate of phosphorus supplementation (equivalent to 86 kg of phosphorus/ha) from the disodium hydrogen orthophosphate soil modifier.



**Figure 7.4** Responses of tomatoes grown for 60 days in the Innisfail Clay treated with different amounts of Minplus<sup>TM</sup> soil conditioner (0, 2.5, 25 t/ha) and an overall high rate of phosphorus from the disodium hydrogen orthophosphate soil modifier. The phosphorus was applied at a rate equivalent to 86 kg of phosphorus/ha, or 955 kg of single superphosphate /ha, which is about 4 times greater than the rate commonly used on crops in the area.



### *Cape Flattery Sand*

A five-fold increase in phosphorus content of the Cape Flattery Sand (5.8 – 24.9 g / g; Table 5.3) resulting from the High application rate of Minplus™ was still insufficient to promote significant plant growth (Fig. 5.3). The result is a clear confirmation, however, of the ability of Minplus™ to supply small amounts of phosphorus to the soil solution. If that phosphorus is not sorbed onto the surfaces of colloids, then it is available to support plant growth. The Cape Flattery Sand has shown that all the tomato plants died in the no Minplus™ – no supplementary phosphorus treatment. With only 2.5 t/ha of Minplus™ applied to the soil, there was enough phosphorus in the soil solution to keep the plants alive, but not enough for them to grow vigorously (Fig. 5.2). The phosphorus constraint was not overcome even at the High rate of application of Minplus™ (Fig. 5.2).

### *Phosphorus fixation and liming*

Applications of lime will address both aluminium toxicity and calcium deficiency in acidic soils, raising the soil pH, and resulting in increased availability of plant nutrients (Fig. 3.2). Unless phosphorus fixation problems in the soil are driven by high levels of exchangeable aluminium, the liming may have no direct influence on phosphorus fixation (Glendinning 1999). Lime certainly provides no extra phosphorus for plant uptake.

On the other hand, Minplus™ can reduce soil acidity by supplying calcium, as does lime, but it is also a source of other elements including, importantly, trace elements and phosphorus, which should make it a preferred soil conditioner for acidic, nutrient-deficient soils in the humid tropics.

Additionally, and perhaps more importantly from an agro-economic perspective, Minplus™ applications reduce the amount of phosphorus fixation of subsequently applied phosphatic fertilisers.

## **7.5 Minplus™ applications and the uptake of nutrients by plants**

Identification of changes in the uptake of nutrients and their incorporation into plant tissue can only really be addressed when the plant tissue analyses have been completed. However, from the change in the leaf colour (Section 6.3.2, above) and the increased vigour of growth (Fig. 7.4), it would appear that increasing Minplus™ applications have increased the uptake of, at least, phosphorus into the plant.

## **7.6 Processes of soil conditioning by Minplus™**

The results of the pot and field trials presented above are complicated to some extent by the interactions between Minplus™ and soil modifier treatments, and their influences on the high content of colloids in the clayey Innisfail Clay. The interactions may relate to the formation of new compounds and precipitates involving phosphorus and aluminium, and competition for adsorption, absorption, and transport sites (Robson and Pitman 1983). Conyers (1999) estimated that over 100 two-way interactions could occur because of the number of elements needed by plants for growth and maturation. The reactions between the elements in Minplus™ and fertilisers (in the field) and soil modifiers (in the pot trial) have impacted on other reactions in the soil and plants, making it difficult to isolate individual effects. Because the soil pH has been raised, other elements in the soil including calcium, magnesium, phosphorus, and some trace elements will have become more available for uptake (Bruce 1988). With higher levels of basic cations, largely calcium and magnesium, derived from Minplus™ applications to the soil, the ECEC was increased, making the soil more fertile.

The field trial has shown that, by allowing the soil to incubate with Minplus™, the subsequent spreading of phosphatic fertilisers produces increased yields in certain species. As the supply of calcium and magnesium have been shown to be not limiting plant growth in the Innisfail Clay (Section 6.3.3), it is the decrease in soil acidity and the increase in the supply of available phosphorus that Minplus™ applications stimulate. Silva (1971) demonstrated similar results from the use of a silicate-based soil conditioner on other soils in India.

### **7.6.1 Basic cations**

The problem with applying lime to some acidic soils is that, while it can decrease soil acidity and increase ECEC, the decrease in acidic cations is usually the result of the exchange sites (vacated by hydrogen, aluminium, and manganese), being dominated by calcium (Hochman *et al.* 1992). The increase in exchangeable cations and

ECEC were, in the pot trial at least, driven by an increase in exchangeable magnesium and a decrease in exchangeable acidic cations.

Field trials on acidic soils in south-east Queensland showed similar results, with calcium occupying most exchange sites, from which Aitken *et al.* (1998) concluded that the application of a very high quality lime on these soils would only increase pH by 0.5 pH units.

A heavy application of Minplus™ has brought about a significant and sustained increase in pH of the topsoil of the Innisfail Clay used in the field trials at the Johnstone College of TAFE (Fig. 4.6). The soils of the pot trial on the Innisfail Clay showed an average increase of 0.7 pH units, with the pH in some being increased by up to 1.2 pH units treatments (Table 6.3), notably where the magnesium and phosphorus soil modifiers had been applied (Burton 1999). Minplus™ has the advantages over lime of supplying some essential micronutrients, and making fertiliser applications of phosphorus more readily available to plants.

## 7.6.2 Phosphorus

In both the field and pot trials, the application of Minplus™ to the soils increased the growth of plants, especially when supplementary phosphorus was applied after the soil had been incubated for at least 10 weeks with the Minplus™. The plant growth response may have been a consequence of the silicate anions occupying sorption sites on the positively charged soil colloids. Thus, when phosphatic anions were applied to the soil as a component of phosphatic fertilisers, they were not immediately attracted to the soil colloids, whose surface charge had been neutralised by the silicate anions. The applied phosphorus should have stayed in the soil solution for longer and have been more readily available for plant uptake.

Recent research results (Ma *et al.* 1997; Cocker *et al.* 1998b), have suggested that some of the improvement in phosphorus uptake seen in the field and pot trials on the Innisfail Clay may be a result of silicates removing exchangeable aluminium from the soil solution by forming insoluble hydroxyaluminosilicates. This would reduce both the availability of aluminium in soil solution, and its ability to bind with any phosphorus applied to the soil to form insoluble aluminophosphates. The result have a similar effect to silicates occupying adsorption sites and forcing the phosphorus to stay in solution and available for plant uptake.

## 7.6.3 Silicon

Essential plant nutrients are those which are required for normal plant growth and reproduction and cannot be replaced in plant metabolic processes by other nutrients (Salisbury and Ross 1992, Ch. 6). Sodium and silicon are regarded as beneficial, not essential nutrients in some higher plants, particularly monocotyledons, but silicon is essential in certain lower plants, such as diatoms (Marschner 1983).

Epstein (1999) found that supplying supplementary silicates to a range of plants, such as sugarcane (*Saccharum* species), rice (*Oryza sativa*), clover (*Trifolium subterraneum*) and ryegrass (*Lolium rigidum*), improved plant growth. The actions of the silicates were thought to improve the balance of other nutrients in the soil, including phosphorus, and to reduce the adverse effects of some heavy metal toxicities and soil salinity. Epstein (1994) also acknowledged that the most important plant nutritional role of the silicates may be in the interactions they have with other elements in the soil and in the plant.

Peaslee and Frink (1969) grew tomatoes in a fine sandy loam, with silicate amendments derived from silicic acid and sodium bicarbonate additives. Plant tissue analyses showed much lower levels of aluminium, manganese, copper, and zinc, but higher levels of available phosphorus in the silicate treatment. The silicate additive was considered by Peaslee and Frink (1969) to be more effective in reducing the influence of toxic elements and improving phosphorus uptake, but no operative mechanisms were proposed. Werner and Roth (1983) studied the influence of silicates in soil and their effects on tomato production. They indicated no growth increases in some of the experiments, but the tomatoes definitely exhibited deficiency symptoms in the reproductive stage when silicates were withheld.

Other studies, mostly using soil-less nutrient culture solutions, have attempted to evaluate the role of silicates in decreasing aluminium toxicity (Cocker *et al.* 1998a). In an experiment using soybeans and a low phosphorus nutrient culture solution, thus removing any influence of soil colloids, Baylis *et al.* (1994) found that silicon formed sub-colloidal inert hydroxyaluminosilicates species, thus relieving aluminium toxicity in the nutrient solution. At lower pH levels, more silicon was required to overcome the toxic effects of aluminium than that

required at a higher pH (Baylis *et al.* (1994). The conclusion was that soluble silicon may decrease aluminium toxicity, and that calcium trisilicate was an effective soil conditioner.

In contrast, Cocker *et al.* (1998a) indicated that the toxic effects of aluminium were not neutralised in the bulk soil solution, but rather in the plant itself, and acknowledged that some aluminosilicates may be slow to form precipitates and so were not detected during their experiments. While a number of alternative mechanisms were mentioned, the proposed model involved root cell walls taking up silicon and aluminium, and forming aluminosilicate compounds which were then stored in the plant, thus detoxifying high soil aluminium contents in the apoplast of the plant.

A third mechanism was put forward by Hammond *et al.* (1995), who considered the silicate-aluminium effect produced greater plant growth because of an improved calcium supply to the plant, at least in barley (*Hordeum vulgare* L.) seedlings at pH 4.5. Silicates appeared to relieve aluminium toxicity and its concomitant negative effects on roots and shoots, resulting in test plant tissues producing similar levels of calcium to the control plants.

It is possible that some of the effects seen from Minplus<sup>TM</sup> applications in the pot trial on the Innisfail Clay were caused by silicates removing exchangeable aluminium from the soil solution, as well as saturating the positively charged sites on colloid surfaces. With more silicates added to the soil in the high rate of Minplus<sup>TM</sup> treatments, there may have been sufficient silicate anions remaining to react with exchangeable aluminium in the soil solution, precipitating insoluble and inert aluminosilicates, even in the presence of soil colloids. Such a mechanism could account for the significant decrease in the acidic cation contents of Minplus<sup>TM</sup>-treated soils (Section 6.3.3).

Because the level of available phosphorus was enhanced in the pot trial using the Innisfail Clay and phosphorus soil modifier, and by phosphatic fertilisers in the field trial, it could be assumed that aluminium was not being removed from the soil solution by the formation of insoluble aluminophosphates. Since the aluminium is not removed from the soil solution, it means that the phosphorus remains in the soil solution for a longer period, hence improving its availability for uptake by plants.

## 8. Longevity of Minplus™ amendments in soils

### 8.1 Introduction

Earlier chapters of this report detailed changes in soil chemical properties resulting from the application of increasing amounts of crushed basaltic rock, locally marketed by Pacific Mineral Developments Pty Ltd as Minplus™, to seven soils representing major soil types in tropical coastal Queensland. Our studies have shown that Minplus™, in acting as a liming material, reduced soil acidity by firstly increasing soil pH, thereby ameliorating soil active acidity, and secondly by attenuating aluminium (Al) dominance of the cation exchange capacity. The latter effect equates to a reduction in the reserve soil acidity, necessary for the achievement of lasting benefits of reduced soil acidity.

By increasing soil pH, Minplus™ caused an increase in soil cation exchange capacity (CEC), the magnitude of the increase being governed by the amount of variable charge components present in the various soils. An increase in CEC allows greater retention of basic plant nutrient cations, namely calcium, magnesium, and potassium.

Minplus™ itself contains appreciable amounts of Ca, Mg, and K in primary mineral forms (Tables 2.1 and 2.2). When the amendment is applied in a finely ground form, sufficient quantities of these elements are solubilised to allow their conversion to exchangeable cations. They then occupy sites on the newly created cation exchange complex, as well as displacing exchangeable aluminium from pre-existing sites. Thus the stocks of calcium, magnesium, and potassium in the soil, in a plant-available form, are increased, the dominance of aluminium in the cation exchange complex is greatly reduced, and aluminium toxicity to plant growth in the soil is eliminated or greatly diminished.

One issue remaining at the completion of this initial study of the beneficial effects of Minplus™ on soils concerns the longevity of the effects observed. In other words, would the high annual rainfall of the humid tropical region (2,500 – 5000 mm) cause the highly desirable conditions achieved from use of Minplus™ as a soil conditioner be short-lived? This would be the case if sufficient quantities of exchangeable basic cations were hydrolysed and leached, causing soil pH to fall, and a reversion to acid soils with low CEC.

### 8.2 Experimental approach

The issue of amendment longevity was addressed in a leaching experiment, in which soil samples selected from the range of incubations of the seven studied soils from the humid tropical lowlands of North Queensland (Table 3.1). The incubated soils were subjected over a six-week period to water additions equivalent to a wet season's rainfall of six months over the region.

The following Minplus™ treatments were chosen for this leaching experiment:

- Zero Minplus™ addition,
- 1 t/ha Standard grade (< 250 m) Minplus™ addition,
- 25 t/ha Standard grade (< 250 m) Minplus™ addition,
- 50 t/ha Superfine grade (< 40 m) Minplus™ addition.

Over the seven soil types, the experiment consisted of 28 leaching columns.

Approximately 1,800 g of soil was placed in specially constructed 15 cm diameter PVC cylinders, so that the height of each soil column was 10 cm, simulating the original soil sampling depth. The soil was supported by a perforated 15 cm diameter perspex disc, and a rayon screen placed between the soil and the disc prevented soil from being lost through the perforations. Water passing through the soil column was channelled from the base of the cylinders to individual collecting vessels. The experiment was carried out in a constant temperature room held at 25 °C.

Within each 'leaching week' in the laboratory, water was added in a single addition on each of five consecutive days, with two 'rest days' to complete the week. The total amount of water added in a week was equivalent to one month's average rainfall at Innisfail. Over a six-week period, the six wettest months of the year were simulated, resulting in a total 'rainfall' of 2,750 mm.

The pH and Electrolytic Conductivity (EC) of the leachates from the daily water additions were analysed in order to estimate the concentrations of soluble salts that had been dissolved by the water passing through the columns of treated soils. A 20 ml subsample of the leachate collected each day was retained for accumulation in a 100 ml 'weekly leachate sample'. In turn, an amount of weekly leachate sample, proportional to the total amount of leachate added in a week, was accumulated to produce a 'bulk leachate sample'. In this way, the concentrations of leached elements in the bulk leachate sample were equivalent to what they would have been if all of the leachate from a column over the entire experiment had been collected. Knowledge of element concentrations in the bulk leachate sample, and of the total amount of water passed through the column, are sufficient to calculate the amounts of each element leached.

The contents of basic cations (for Ca, Mg, K, Na) and of aluminium were determined in the bulk leachate solutions by atomic absorption spectrometry.

At the completion of the leaching phase, soil samples were collected from each of the columns. Three PVC tubes (I.D. = 16 mm) were pushed through the entire length of the column, and the soil entrapped therein was then extruded with a 16 mm rod. The three resulting soil cores were bulked and dried for analysis, namely pH, CEC, exchangeable Ca, exchangeable Mg, exchangeable K, exchangeable Na, and exchangeable (H + Al).

## **8.3 Results of the leaching experiments**

### **8.3.1 Electrical conductivity of the daily leachates**

Electrical conductivity measurements were performed on the daily leachate samples to identify significant events such as pulses of salt movement from the column, or the point at which no further leaching losses might be expected. The pattern of change in electrical conductivity with time was similar for all seven soils. Figure 8.1 depicts this relationship for the basaltic Pin Gin Soil and the Galmara Soil formed on metamorphic rocks.

The highest electrical conductivity values were recorded in the first leachate volume collected from each column. They decreased rapidly to constant values after the addition of the equivalent of the first 'month' of rainfall in some soils, and certainly after two 'months' for all the soils (Fig. 8.1). The plateau values after these two months were in the vicinity of 100 S/cm, a low conductivity value, indicating that only small amounts of elements were being leached from the soil samples. Within a soil type, the magnitude of the electrical conductivity of the leachate was related to the amounts of Minplus<sup>TM</sup> that had been initially applied, as would be expected.

The electrical conductivity patterns of the daily leachate collections, as illustrated in Fig. 8.1, clearly indicated that there would be little point in continuing water application past the equivalent of six months of leaching in the field.

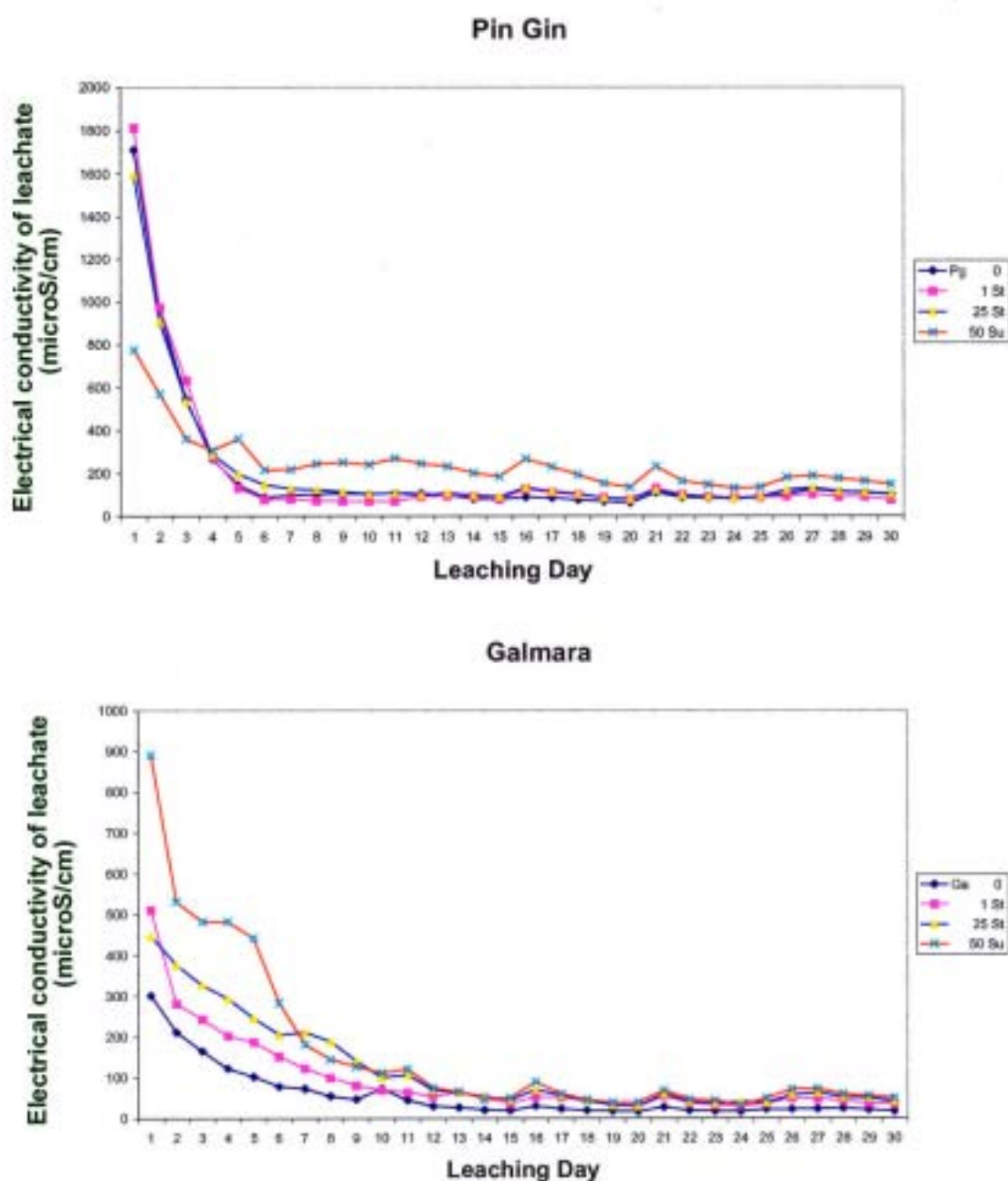


Figure 8.1 Electrical conductivity (  $\mu\text{S/cm}$ ) of leachates collected daily from Minplus<sup>TM</sup>-treated samples of the Pin Gin and Galmara Soils over the course of a laboratory leaching experiment designed to simulate leaching from the soil in the field under the rainfall of one wet season.

Abbreviations used in the legends of each part of the figure indicate the rates of applications of Standard (St;  $< 250 \text{ m}$ ) or Superfine (Su;  $< 40 \text{ m}$ ) grades of Minplus<sup>TM</sup> in t/ha.

### 8.3.2 pH of the daily leachates

The pattern of changes in leachate pH with time showed some interesting trends common to all seven soils, and once again the Pin Gin and Galmara Soils are used to illustrate them (Fig. 8.2). As expected, the pH was higher in leachates from Minplus™-amended samples, and increased in accordance with application rate. As the experiment progressed, leachate pH values rose, possibly in response to a steady increase in reducing conditions as the soil columns became more compact, and leaching rates slowed. This would have the effect of slowly causing oxygen availability within the column to become limiting.

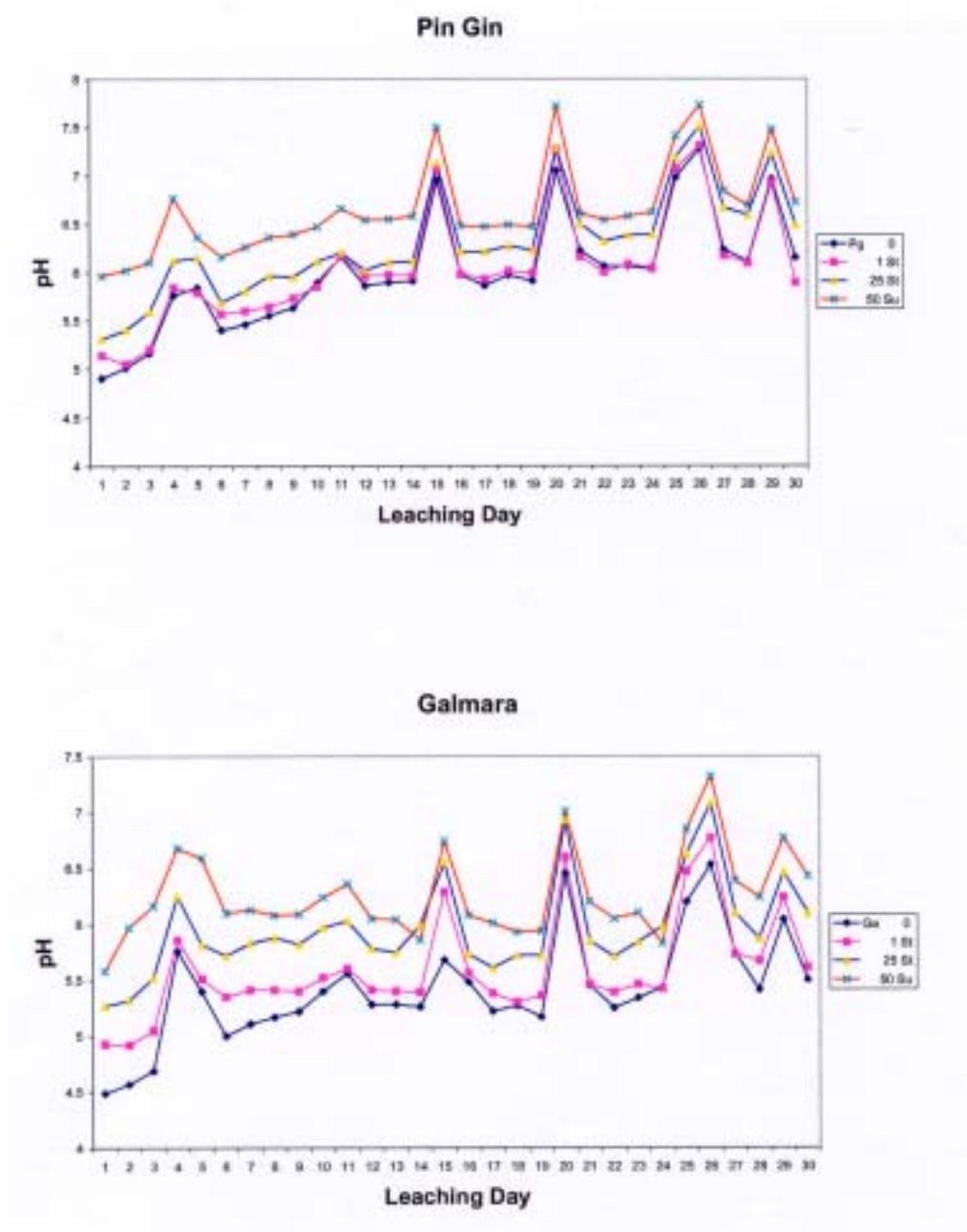


Figure 8.2 pH of leachates collected daily from Minplus™-treated samples of the Pin Gin and Galmara Soils over the course of a laboratory leaching experiment designed to simulate leaching from the soil in the field under the rainfall of one wet season.

Abbreviations used in the legends of each part of the figure indicate the rates of applications of Standard (St; <250 m) or Superfine (Su; <40 m) grades of Minplus™ in t/ha.

The pH 'spikes' apparent at the end of each simulated week (5 actual days) of leaching are attributed to the same phenomena. Reducing conditions could develop after five continuous days of leaching, but the following two 'rest' days would allow oxygen to re-enter the soil column.

The patterns depicted in Fig. 8.2 are no doubt attributable to the artificial nature of the experiment, with large quantities of water being added to the soil over a shortened time span. It is interesting to surmise, however, that at least in the less freely-draining soils, continuous heavy rain over prolonged periods might produce similar anoxic conditions in the field, and a rise in soil pH. In variable charge soils, this would result in a temporary rise in CEC, and therefore provide some protection against cation leaching loss, when most needed.

### 8.3.3 Cations in the leachates

The amounts of basic cations (Ca, Mg, K, Na) present in the bulk leachate samples are summarised in Table 8.1. As explained above, these values are the same as would be obtained if the total volume of water passing through the column had been collected and analysed. The actual amounts of each element removed from the soil are calculated by multiplying its concentration in the leachate by the total volume of leachate collected from that soil.

The units used in Table 8.1 are commonly employed because they allow easy manipulation in cation exchange calculations. However, a clearer picture of their significance to the longevity of Minplus<sup>TM</sup> amendments in treated soils emerges if the amounts of leached cations are expressed as kg/ha. This has been done, and the values compared with the amounts present as exchangeable cations in the soils before leaching was initiated. These comparisons are best appreciated in the form of plots of cations dissolved in the leachates against contents of exchangeable cations in the 28 soils studied (7 soil series x 4 Minplus<sup>TM</sup> treatments; Fig. 8.3). It should be remembered that the exchangeable cation content of the soil does not represent the total amount of soil cations in the Minplus<sup>TM</sup>-treated soil, but only those present in plant-available form. As explained in Section 3.3 above, the application of Minplus<sup>TM</sup> to soils will produce relatively large reserve supplies of cations in an insoluble form, which is essentially unavailable to growing plants.

Only a small fraction of the exchangeable Ca in the 28 unleached soils has been mobilised into the leachates; the proportion is somewhat larger with respect to Mg (compare Figs 8.3 a, 8.3 b). These conclusions are reached by examining the position of the plotted points in relation to the 1:1 line. On the other hand, relatively greater proportions of K were leached, and in the case of Na, amounts leached were greater than that present in exchangeable form (Figs 8.3 c, d). These results are consistent with known bonding strengths of cation adsorption to charged surfaces, decreasing in the order  $\text{Ca} > \text{Mg} > \text{K} > \text{Na}$  (Brady and Weil 1996, p. 336).

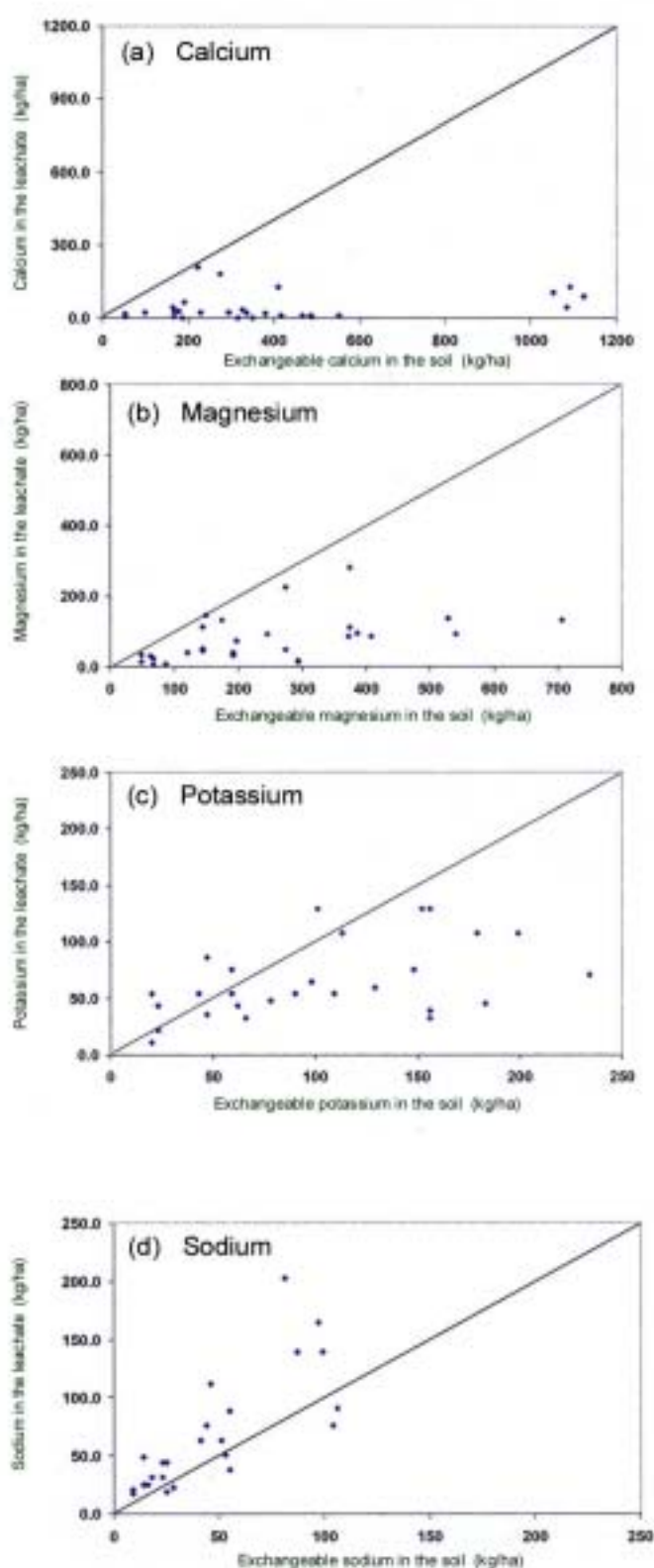
The escape of applied nutrient cations from the 0-10 cm layer of soil is not necessarily undesirable, particularly if the release occurs slowly and results in enrichment of sub-soil horizons. The effect would be to encourage plant root proliferation into cation-deficient subsoils. These aspects need to be directly explored in field-based studies.



**Table 8.1** Amounts of basic cations (mmol./litre) leached by the equivalent of one wet season's rainfall from the 7 studied soils of the humid tropical Innisfail – Tully area, North Queensland, to which different amounts of Standard and Superfine grades of Minplus™ had been applied.

Soil	Minplus™ treatment *	Amounts of basic cations in bulk leachate samples (mmol./litre)			
		Calcium	Magnesium	Potassium	Sodium
Pin Gin	0 t/ha	0.19	0.26	0.12	0.07
	1 t/ha St	0.23	0.28	0.10	0.08
	25 t/ha St	0.16	0.40	0.10	0.12
	50 t/ha Su	0.08	0.44	0.14	0.26
Mundoo	0 t/ha	0.03	0.16	0.05	0.05
	1 t/ha St	0.03	0.20	0.06	0.06
	25 t/ha St	0.02	0.24	0.07	0.10
	50 t/ha Su	0.03	0.56	0.11	0.24
Innisfail	0 t/ha	0.12	0.12	0.05	0.05
	1 t/ha St	0.38	0.44	0.08	0.07
	25 t/ha St	0.33	0.68	0.05	0.14
	50 t/ha Su	0.23	0.85	0.10	0.32
Tyson	0 t/ha	0.08	0.09	0.05	0.04
	1 t/ha St	0.05	0.07	0.04	0.04
	25 t/ha St	0.04	0.22	0.06	0.10
	50 t/ha Su	0.04	0.28	0.07	0.22
Galmara	0 t/ha	0.01	0.04	0.04	0.03
	1 t/ha St	0.03	0.10	0.05	0.05
	25 t/ha St	0.04	0.34	0.07	0.10
	50 t/ha Su	0.05	0.40	0.12	0.26
Tully	0 t/ha	0.11	0.28	0.06	0.05
	1 t/ha St	0.07	0.24	0.06	0.06
	25 t/ha St	0.06	0.52	0.08	0.14
	50 t/ha Su	0.03	0.75	0.10	0.32
Kurrimine	0 t/ha	0.01	0.02	0.02	0.04
	1 t/ha St	0	0.02	0.01	0.05
	25 t/ha St	0	0.04	0.03	0.12
	50 t/ha Su	0	0.05	0.05	0.22

\* 'St' = Standard grade of Minplus™ (< 250  $\mu$ m); 'Su' = Superfine grade of Minplus™ (< 40  $\mu$ m).

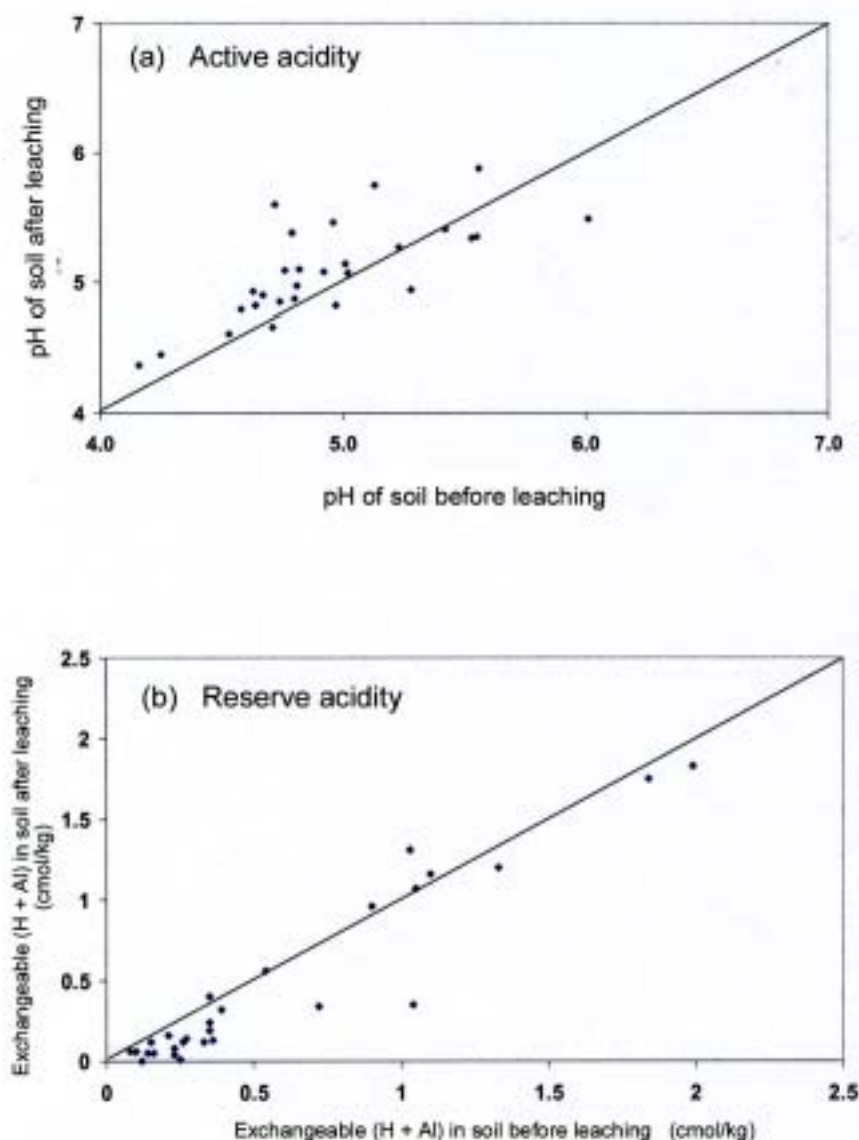


**Figure 8.3** Amounts of basic cations leached from the 28 Minplus<sup>TM</sup>-treated soils (7 soil series x 4 Minplus<sup>TM</sup> treatments: 1, 5, 25, 50 t/ha) compared with the amounts of exchangeable basic cations present in each of the soils prior to leaching in the laboratory. All results are expressed in kg/ha.

### 8.3.4 Changes in soil acidity induced by leaching

The pH values of soil samples after leaching were generally higher than values recorded prior to leaching. This is best shown by plotting post-leaching soil pH against pre-leaching soil pH (Fig. 8.4a). The majority of points lies above the 1:1 line and this may be attributable, as discussed in Section 8.3.2 above, to a residual rise in pH resulting from anoxic conditions induced in the experiment.

Similarly, the amounts of reserve acidity in the soils (estimated by the contents of exchangeable acidic cations, H + Al) were not greatly altered by leaching (Fig. 8.4b). In fact, most of the points fall below the 1:1 line, indicating small reductions in exchangeable acidity resulting from the modest increases in soil pH.



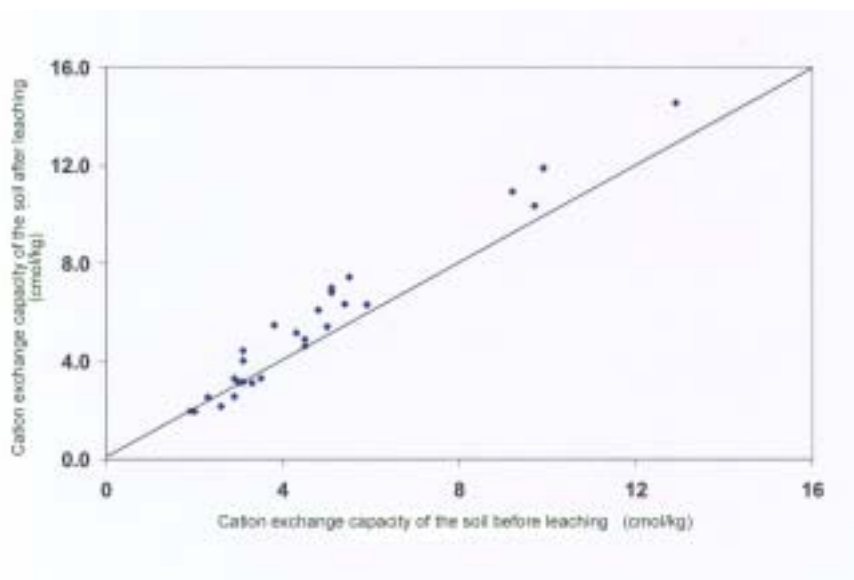
**Figure 8.4** The effect of experimental laboratory leaching on the active and reserve acidity of 28 studied soils (7 soil series  $\times$  4 Minplus<sup>TM</sup> treatments: 1, 5, 25, 50 t/ha).

(a) active acidity: soil pH (pH units),

(b) reserve acidity: exchangeable acidic cations (H + Al; cmol/kg).

### 8.3.5 Changes in cation chemistry of the leached soils

A comparison between CEC values before and after leaching is presented in Fig. 8.5. The points lie just above the 1:1 line, so there has been an overall small increase in CEC as would be expected in variable charge soils if soil pH had risen. This is a significant finding as the lack of any hint of a reduction in CEC following leaching indicates that there is a degree of permanency in the ability of Minplus™ to increase the capacity of this suite of highly weathered soils to retain plant nutrient cations against leaching forces.



**Figure 8.5** Cation exchange capacities of 28 highly weathered soils of the humid tropics of North Queensland (7 soil series x 4 Minplus™ treatments: 1, 5, 25, 50 t/ha) before and after experimental leaching in the laboratory with the equivalent of one wet season's rainfall.

Changes induced by leaching in the contents of the four exchangeable basic cations are summarised in Fig. 8.6. The closeness of fit to the 1:1 line for exchangeable calcium (Fig. 8.6 a) demonstrates that the augmentation of this important plant nutrient by Minplus™ applications has not diminished, despite the addition of large quantities of water to the columns. In the case of exchangeable magnesium (Fig. 8.6 b), the majority of points lie below the 1:1 line, indicating some reduction by leaching in the contents of this element across the Minplus™-treated soils. It should be pointed out however, that despite some losses, an average of 94% of the exchangeable magnesium present in the soil prior to leaching has been preserved. The small leaching losses from the soil in magnesium were reflected in the elevated values for this element in the leachates (Fig. 8.3).

The reductions in exchangeable potassium following leaching were more serious (Fig. 8.6 c), with an average of 53% of the pre-leaching potassium content of the soils being maintained. Even greater proportions of exchangeable sodium were lost (Fig. 8.6 d), but because of the limited requirement for this element in plant nutrition, the loss of sodium is not considered to be a problem.

The inability of the monovalent potassium and sodium to compete with divalent calcium and magnesium for cation exchange sites in most soils is well known. The amounts of exchangeable potassium deemed necessary for healthy plant growth are much lower than for calcium and magnesium, so it is not clear whether the application of Minplus™, followed by leaching will satisfy plant requirements. This aspect will require field-based studies.

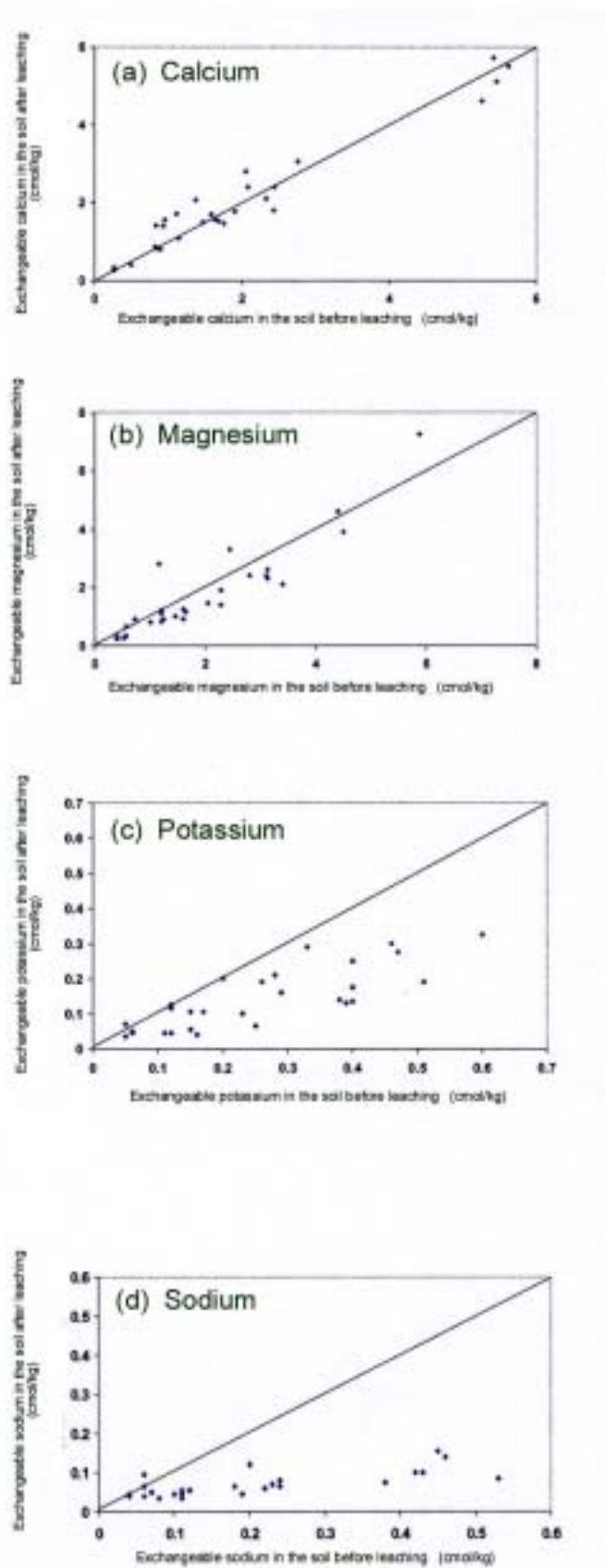


Figure 8.6 Contents of exchangeable basic cations in 28 highly weathered soils of the humid tropics of North Queensland (7 soil series x 4 Minplus™ treatments) before and after experimental leaching in the laboratory with the equivalent of one wet season's rainfall.

## 8.4 Conclusions

Extremely encouraging results have been obtained from a laboratory leaching experiment in which the equivalent of one wet season's rainfall from Innisfail has been leached through Minplus<sup>TM</sup>-treated columns of a suite of highly weathered soils. Minplus<sup>TM</sup> applications have effected a significant increase in the cation exchange capacity of the soils, which has been sustained against the leaching effects of one wet season's rainfall.

After leaching, the soils showed no diminution in the increased amounts of exchangeable calcium that have been derived from the Minplus<sup>TM</sup> treatments. Similarly, some 94% of the exchangeable magnesium, and a lesser amount of exchangeable potassium (53%), has been retained in the leached soils.

These results suggest that some of the important benefits of Minplus<sup>TM</sup> applications to soils may be retained against leaching of rainfall over a number of wet seasons. Continued monitoring of changes in the field trials that have been established on the Innisfail Clay (Chapter 6) will provide a field verification of these findings on at least one of the studied soils. Other long-term trials are needed on other soils and under different vegetation covers to confirm the longevity of the benefits of Minplus<sup>TM</sup> applications to a wider range of soils and farming systems.

# 9. Conclusions

## 9.1 Scientific results

The present study has shown that the application of Minplus™ induced changes in the chemical properties that are reflected in changes in plant growth in a range of soils from the humid tropical lowlands of North Queensland. Two contrasting soils, the neutral Cape Flattery Sand and the strongly acidic, clay-rich Innisfail Clay, have been studied in considerable detail. Growth responses evident in tomato and grass indicator plants in nutrient omission and nutrient addition pot trials have allowed an elucidation of the soil processes involved in the use of Minplus™ as a soil conditioner.

The present project has confirmed that the main soil constraints to growth are those typical of many of the highly weathered soils of the humid tropics of northeastern Australia, including:

- low cation exchange capacity of the soil, which reduces the capability of the soil to retain cations against leaching processes and to supply cations to plants,
- low basic cation supply in the soil leading to deficiencies or imbalances in supply of macronutrients that are essential for adequate plant growth (especially calcium, magnesium, and potassium),
- strong soil acidity,
- strong phosphate fixing capacity of particular soils.

It was found that these constraints can be overcome or significantly reduced with the application of Minplus™ at a rate of at least 2.5 t/ha but higher rates, up to 25 t/ha, were found to produce more dramatic plant growth responses. While Minplus™ acts as an extremely effective conditioner of highly weathered soils, it does not contribute any nitrogen, and can supply only minor amounts of phosphorus and sulphur to the soil. These essential elements must be applied separately to soils that are conditioned by Minplus™.

The research results showed that increases in the fertility of Minplus™-treated soils are brought about by the soil conditioner's ability to increase the cation exchange capacity of the soil. Columns of Minplus™-treated soils were subjected to leaching in the laboratory using the equivalent of a year's rainfall at Innisfail. The results suggested that more than 85% of the improvement in the cation exchange capacity of the soil may be retained in the leached soil. The extent of the retention of soil conditioning benefits derived from applications of Minplus™ are still being monitored at the project's field experimental site at the Johnstone College of TAFE, Innisfail.

Our results to date, and anecdotal evidence from the farming community of the Innisfail area suggest that it is likely that enhanced crop growth might be obtained from the retention of benefits of Minplus™ in the soil from one growing season to the next. Hence, some of the beneficial effects of successive light, and less expensive applications of Minplus™ may cumulate in the soil over a period of years to produce results that may be expected from single heavy applications.

Careful consideration would have to be given to the application of high rates of Minplus™ to soils which have no magnesium deficiency, otherwise extra calcium may have to be applied to maintain an effective calcium : magnesium ratio.

## 9.2 Efficacy of Minplus™ as a soil conditioner

In summary, the results of the research outlined in the present report has demonstrated that Minplus™ has the capacity to:

- rejuvenate the mineral and chemical properties of highly weathered soils;
- increase negative charge in the soil;
- increase the cation exchange capacity of the soil;
- enhance the ability of soils to retain cations in the soil;
- enhance the ability of soils to supply cations to plants;
- reduce soil acidity, similarly to the action of lime, but sustained against soil leaching in high rainfall terrains over a long time period;
- neutralise soil acidity without the liberation of greenhouse gases, unlike lime which releases 400 kg of carbon dioxide from every tonne of lime applied to the soil;
- reduce phosphorus fixation capacity of the soil, so that phosphates added in fertilisers are kept in soil solution, and are therefore more readily available for plant nutrition;
- provide silicon to the soil in an available form for uptake into plant cells, which is thought to result in improved plant vigour and quality;
- enhance plant growth in difficult, highly weathered soils whose properties combine to inhibit crop production.

Our studies have shown that Minplus™, in acting as a liming agent, reduces soil acidity by firstly increasing soil pH, thereby ameliorating soil active acidity, and secondly by attenuating aluminium dominance of the cation exchange complex of the soil. The latter effect equates to a reduction in the reserve soil acidity, necessary for the achievement of lasting benefits of reduced soil acidity.

By increasing soil pH, Minplus™ caused an increase in soil cation exchange capacity, the magnitude of the increase being governed by the amount of variable charge components present in the various soils. An increase in cation exchange capacity allows greater retention of basic plant nutrient cations, namely calcium, magnesium, and potassium. Minplus™ itself contains appreciable amounts of these elements in primary mineral forms. When the amendment is applied in a finely ground form, sufficient quantities of the elements are solubilised to allow their conversion to exchangeable cations. They then occupy sites on the newly created cation exchange complex, as well as displacing exchangeable aluminium from pre-existing sites. Thus the stocks of calcium, magnesium, and potassium in the soil, in a plant-available form, are increased, the dominance of aluminium in the cation exchange complex is greatly reduced, and aluminium toxicity to plant growth in the soil is eliminated or greatly diminished.

The longevity of the beneficial effects of Minplus™ in the seven studied soils of the Innisfail–Tully area was investigated in a laboratory leaching study of Minplus™-treated soils which were subjected to the equivalent of one wet season's rainfall at Innisfail (2,750 mm) applied over a six week period.

Minplus™ applications effected a significant increase in cation exchange capacity of all the soils studied, which was sustained against the leaching processes. After leaching, the soils showed no diminution in the increased amounts of exchangeable calcium that were derived from the Minplus™ treatments. Similarly, some 94% of the exchangeable magnesium content, and a lesser amount of exchangeable potassium (53%), were retained in the leached soils.

These results suggest that some of the important benefits of Minplus™ applications to soils may be retained against leaching of rainfall over a number of wet seasons. Continued monitoring of changes in the field trials that have been established on the Innisfail Clay will provide a field verification of these findings on at least one of the studied soils. Other long-term trials are needed on other soils and under different crop and vegetation covers to confirm the longevity of the benefits of Minplus™ applications to a wider range of soils and farming systems



### 9.3 Minplus™: prospects and opportunities

Use of Minplus™ as a soil conditioner in highly weathered soils is expected to deliver:

- improved plant growth in acidic, highly weathered soils of low fertility – especially those of the humid tropics;
- reduced fertiliser use in acidic, iron-rich soils with strong phosphorus-fixing properties;
- new farming strategies to ensure more sustainable uses of soil resources and fertilisers.
- import replacement as a result of diminished use of high-cost imported fertilisers;
- reduced environmental hazards from decreased use of agricultural lime;
- reduced environmental hazards from decreased erosional losses of nutrients from farmlands and their deposition in sensitive natural wetlands and nearshore marine systems.

Hence, there are business opportunities to develop and market a product that :

- is entirely natural and is certified for use in organic farming systems;
- has the potential to increase significantly crop health and yields;
- reduces farming input costs in lower rates of application of fertiliser, and possibly pesticides;
- reduces the social, economic, and environmental impact of algal blooms and other evidence of high nutrient levels in waterways downstream of agricultural activities;
- is a source of calcium cations that may provide a tool that may be used in the amelioration of sodic soils;
- provides import replacement through the need for less fertiliser to sustain plant production on soils that have been treated with Minplus™ applications. This point is particularly significant in Far North Queensland, where fertiliser (70,000 tonnes in 1999) is second only to fuel in the scale of imports into the regional economy through the Port of Cairns.

### 9.4 Future research directions

Although the present project has provided answers to a number of research questions, there are still many more questions to be answered. The major issues remaining are derived from an examination of the anecdotal evidence of benefits thought by product users in the Innisfail area to accrue from the use of Minplus™ (Section 1.3.3).

They include:

- hardier plant foliage,
- faster plant growth,
- greater plant resistance to pests and diseases,
- enhanced chemical analyses of soil samples,
- increased friability of the soil,
- bigger, stronger, and healthier roots of tree crops,
- reduced plant tipping in bananas and other tree crops during cyclonic winds,
- more vigorous soil animal populations,
- increased capacity of the soil to retain, in the root zone of the plants, moisture and nutrients applied as fertilisers,
- improved crop yields and produce quality.

In the longer term, it is envisaged that a manual will be developed that will set out the most appropriate ways to use Minplus<sup>TM</sup>, in conjunction with conventional N-P-K fertilisers to produce optimal growth in a range of crops on the highly weathered soils of northern Australia. Such a knowledge base will permit research to be carried out confidently in other regions, and the results extended more widely.

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