Introduction

In Australia, irrigated cotton is largely produced on cracking clay soils (black earths and grey brown clays) (McKenzie 1998; NLWRA 2002) or Vertosols (Isbell 1996). While a value has not been estimated for economic losses due to soil sodicity in cotton farming systems, soil maps and surveys of Australia suggest that the surface and/or the subsoil in a majority of cotton growing regions in Australia is sodic (Northcote and Skene 1972; Naidu *et al.* 1995; McKenzie 1998). Cotton produced on sodic soils commonly exhibits reduced growth and elevated plant concentrations of Na and reduced concentrations of K and P, when compared to cotton produced on non-sodic soils (Rochester Unpublished).

Sodicity has a negative effect on the physical properties of soils. As a consequence of the process of dispersion, sodic soils generally have low hydraulic conductivities (Quirk and Schoefield 1955), reduced infiltration rates (Kazman *et al.* 1983) and low plant available water capacities (Gardner *et al.* 1984). Sodic soils are also frequently characterised by high soil strength (So and Aylmore 1993) and a susceptibility to waterlogging events (Jayawardane and Chan 1994). In sodic soils, the least limiting water range (LLWR) can thus be very narrow, with crops suffering aeration stress after irrigation or rainfall and excessive soil strength and water stress becoming limiting early in the drying cycle (Jayawardane *et al.* 1987). These physical properties of sodic soil have the potential to limit the growth and nutrient accumulation of cotton by reducing root growth and function.

Sodic soils are also frequently characterised by the chemical properties of elevated exchangeable and solution concentrations of Na and high pH values (Naidu *et al.* 1995). The chemical properties of sodic soils have the potential to limit the growth and nutrient accumulation of cotton by inducing Na toxicities and deficiencies of micronutrients in plant tissues.

Due to the complex set of interactions that control the physical and chemical responses of soils to sodic conditions in field production situations, the effects of sodicity on the growth and nutrition of cotton crops has not been well quantified. Additionally, the development of appropriate strategies for the management of cotton crops produced on sodic soils, has been hampered by uncertainty regarding the principal mechanisms by which sodic soils limit cotton performance The aim of this project was to better quantify the effects of sodicity on the growth and nutrition of cotton and to determine the principal mechanisms responsible for these effects. The outcomes of this research are reported in the following chapters of this thesis:

Chapter One reviews the published literature on the physical and chemical characteristics of sodic soils and the implications of sodicity for the growth and nutrition of cotton and other plants.

Chapter Two reports investigations on the growth and nutritional responses of cotton to sodic soils in a commercial field production situation. The results of this chapter were used to inform the design of subsequent glasshouse experiments.

Chapter Three outlines the processes carried out to validate two methods used in subsequent glasshouse experiments. Firstly, a method is described that can be used to create soils with a range of exchangeable sodium percentage values (ESPs), in order to minimise the confounding of experimental results with variation in other soil properties and extremes of salinity and pH. Secondly, the effects of polyacrylamide (PAM) on the availability of nutrients in soils was investigated, in order to determine if PAM application is an appropriate tool for use in overcoming the poor physical condition of sodic soils in glasshouse experiments.

Chapter Four reports investigations on the growth and nutritional responses of cotton to nutrient solution concentrations corresponding to those found in sodic Grey Vertosols. This experiment quantifies the effects of sodic soil solution chemistry on cotton growth and nutrition under aerated conditions, without the confounding of these results with soil physical condition.

Chapter Five reports investigations on the effects of soils with a range of ESP values on the growth and nutrient accumulation of cotton. Treatment of some of the soils with PAM allows the separation of the effects of soil physical and chemical characteristics.

Chapter Six examines the effects of sodicity on the recovery of cotton plant function after a period of waterlogging and investigates the effects of waterlogging on the nutrient accumulation of cotton grown in soils with a range of ESP values.

Chapter Seven investigates the nutritional responses of cotton to waterlogging in nutrient solution concentrations corresponding to those found in sodic soils. This experiment quantifies the effects of sodic soil solution chemistry on the responses of cotton to waterlogging, without the confounding of these results with soil physical condition.

The practical implications of this research and future research directions are outlined in Chapter Eight.

Chapter 1. A review of sodic soils and cotton production systems

1.1. Sodic soils and Australian cotton production: an overview

1.1.1. *Sodic soils: a definition*

Sodic soils are generally defined by the parameter of exchangeable sodium percentage (ESP). ESP can be calculated as follows (concentrations in $cmol_c\ kg^{-1}$);

$$ESP = \frac{(100 \times \text{Exchangeable Na})}{\text{Cation Exchange Capacity}}$$

The sodicity of irrigation water and soil solutions is defined using the parameter of Na adsorption ratio (SAR). SAR can be calculated as follows (concentrations in mM);

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}}$$

No universally accepted critical ESP for sodic soils exists. The current definitions for sodic soils are based upon the critical ESP at which soil dispersion occurs, with the critical value ranging between 5% (McIntyre 1979) and 15% (USSL 1954). In Australia, Northcote and Skene (1972) assigned three classes of sodicity: non-sodic (ESP <6%), sodic (ESP 6%-15%) and strongly sodic (ESP >15%). In the Australian Vertosols used for cotton production McKenzie (1998) suggests the use of an ESP of 5% to delineate sodic soils, because ESPs as low as 2 can have detrimental effects on the structure of these soils under conditions of low electrical conductivity (Cook *et al.* 1992).

These conflicting sodicity classifications demonstrate that the behaviour of soils in the presence of exchangeable Na differs according to numerous factors. These factors include the electrical conductivity (EC) of the soil solution and leaching water, soil texture, clay mineralogy, organic matter content, position within the profile, pH and the suite of accompanying cations (McKenzie *et al.* 1993). Thus, the sodicity classification of a particular soil needs to be determined according to its behaviour in the environment and corresponding limitations to productivity, rather than using a critical ESP value.

1.1.2. *The distribution of sodic soils in Australia*

The Na present in Australian soils comes from a number of different sources, including incorporation of marine salts into precipitation, aeolian transport, mineral weathering and saline groundwater (Chartres 1993). Additionally, irrigation can contribute significant quantities of Na to soil profiles (Rengasamy and Olsson 1993).

The National Land and Water Resources Audit (2002) estimated that 23% of Australia is occupied by sodic soils (Figure 1-1), while saline soils occupy just 1% of the Australian land area (Figure 1-2). The value of the agricultural productivity lost due to salinity in Australia has been estimated at $200 million annually, while a figure of $1 billion has been estimated for sodicity (NLWRA 2002). Loveday (1980) and Rengasamy and Olsson (1991) suggested that the area of sodic soil in Australia is increasing due to the re-use of untreated saline groundwater and rising saline groundwater. McKenzie (1991) suggested that surface sodicity is also increasing in cultivated soils due to deep tillage and land levelling bringing subsoil sodicity closer to the surface and due to the loss of top-soil by wind and water erosion.

In NSW, sodic soils are concentrated in the more arid western areas and in the northern cropping regions west of the Great Dividing Range. Alkaline cracking clays, with uniform texture profiles are a dominant type of sodic soil but Sodosols, with a sodic B horizon, are also common (Hubble 1984).

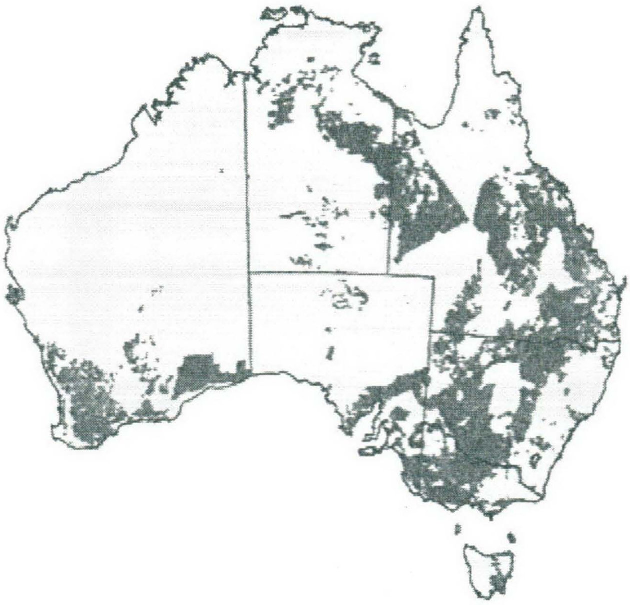


Figure 1-1 The locations in Australia where sodic soil conditions constrain agricultural production (NLWRA 2002).

Figure 1-2 The locations in Australia where saline soil conditions constrain agricultural production (NLWRA 2002).

1.1.3. *The Australian cotton industry and sodicity*

In 1998, the Australian cotton industry occupied an area of 535,400 ha (NLWRA 2002), but this area changes on an annual basis, due largely to variable seasonal climatic conditions. The majority of Australia's cotton is produced in inland southern/central Queensland and New South Wales but research is being conducted in northern Western Australia to assess the viability of expanding cotton production in this area (Figure 1-3).

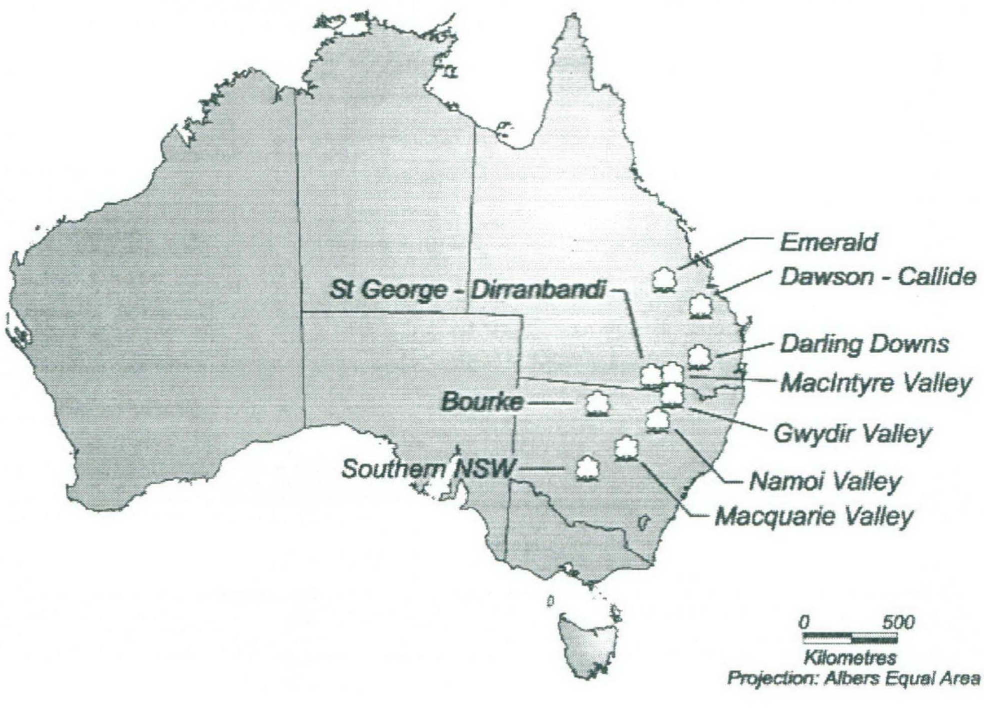


Figure 1-3 A map of the major cotton producing areas in Australia (NLWRA 2002).

In Australia, irrigated cotton is largely produced on cracking clay soils (black earths and grey brown clays) (McKenzie 1998; NLWRA 2002) or Vertosols (Isbell 1996). While a value has not been estimated for economic losses due to soil sodicity in cotton farming systems, soil maps and surveys of Australia suggest that the surface and/or the subsoil in a majority of cotton growing regions in Australia are sodic (McKenzie 1998; Northcote and Skene 1972).

The production efficiency of the Australian cotton industry has increased significantly over the last two decades, with average yields rising from 1169 kg/ha in the season 1980/81 to a world record average of 2038 kg/ha in season 2004/2005 (ICAC 2005). This increase can be attributed to genetic crop improvement and advances in production techniques, such as irrigation, agronomy, integrated pest management and the nutritional management of the crop (Constable and Bange 2006). As yield potential of Australian cotton production systems has increased, so too has the potential for sodic soil conditions to limit cotton performance.

1.2. The physical properties of sodic soils

1.2.1. *Clay dispersion in sodic soils*

Clays are those mineral particles in the soil with a diameter of less than 0.002 mm. As such, they make up a large proportion of the internal surface area of the soil and contribute significantly to many soil physical and chemical properties (Norrish and Pickering 1983). The stability of the aggregates in a soil depends upon the relative strength of the forces that exist between the clay fraction of the soil and the soil solution (Sumner 1993).

The clay particles in dry aggregates are linked together by strong attractive forces and the distance between adjacent clay particles is generally less than 1 nm (Rengasamy and Olsson 1991). When a dry soil aggregate is hydrated however, interactive forces lower the potential energy of the water molecules, with the resultant release of energy being used partially for the structural transformation of the clay aggregate and partially in the release of heat (Rengasamy and Olsson 1991). The structural transformation of the aggregates that occurs upon their hydration may include swelling, slaking and dispersion. Swelling is an increase in the volume of a soil, as a homogeneous body. Slaking involves the breaking down of soil aggregates, along planes of weakness, into smaller particle groups of >20 μm. Dispersion involves the breakdown of a soil into particles of <2 μm, which then diffuse through the dispersing solution (Churchman *et al.* 1993). Soil factors which affect the degree of slaking that occurs upon the hydration of a soil are largely related to the extent of the bonding of the soil with organic substances and inorganic materials such as carbonates (Ingles 1968). The dominant soil factor contributing to dispersion is exchangeable Na but non-soil factors, such as the application of external stresses, also contribute (So and Cook 1993).

The diffuse double layer (DDL) is the interface between the surface of a clay mineral and the soil solution and consists of the negative charge of the clay surface and the cations in the soil solution. The thickness of the DDL is smaller when dominated by divalent (e.g. Ca^{2+}) or trivalent (e.g. Al^{3+}) ions, but larger where monovalent (e.g. Na^{+}) ions predominate. The thickness of the DDL is also reduced by solutions with high electrolyte concentrations (Rengasamy and Sumner 1998). When a soil has a high ESP and the electrolyte concentration of the soil is sufficiently low, the distance between clay particles upon hydration increases to such an extent that the particles begin to separate, resulting in accentuated swelling. If the distance between adjacent clay particles increases beyond 7 nm upon further hydration, either spontaneously or due to additional mechanical input, the soil will undergo dispersion, with the clay particles becoming independent of each other (Rengasamy and Sumner 1998). When sodic soils disperse and then dry, the result is the formation of a massive structure, without any hierarchical arrangement of clay particles into micro and macro-aggregates (Barzegar *et al.* 1994).

1.2.2. *The influence of soil properties on clay dispersion*

So and Cook (1993) demonstrated that the dominant factor contributing to clay dispersion in sodic soils is the concentration of Na in the soil relative to the concentrations Ca and Mg. The extent of soil dispersion occurring at a given soil ESP however, also depends upon the EC, clay mineralogy, pH, organic matter content and other cations of the soil. For this reason, each soil will have a unique relationship between ESP, EC and dispersion and it is impossible to divide soils into sodic and non-sodic classes based solely on ESP. The sodicity classification of each soil ideally should be determined individually, although some approximate and generally applicable relationships exist.

Electrical conductivity

Other than exchangeable Na content, the EC of the soil solution is the most influential factor in the dispersion of sodic clay soils (Levy *et al.* 1998). Dispersion occurs when soil solution water is forced to move into the double diffuse layer, in response to an electrochemical gradient. Thus, low soil solution EC favours the dispersion of clay minerals, as water is more easily drawn from the low EC of the soil solution to the higher EC of the DDL (Loveday 1976; Quirk and Schoefield 1955).

Rengasamy *et al.* (1984) demonstrated the importance of the concentration of ions in the soil solution to the stability of red-brown earths under sodic conditions. These authors illustrated that increases in total cation concentration (TCC) in the soil solution increased soil stability while increases in soil solution SAR decreased soil stability. Shainberg *et al.* (1992) also demonstrated the potential for soils with high TCC (3.31 mmol L^{-1}) to maintain their hydraulic conductivity at all but the highest sodicity levels. In contrast, soils with very low ESP values demonstrated significant reductions in hydraulic conductivity with the application of water containing a TCC of only 0.7 mmol L^{-1}.

The relationship between salinity, sodicity and dispersion is commonly summarized by the electrochemical stability index (ESI). ESI can be calculated as follows:

$$ESI = \frac{EC_{1:5}\ (dS/m)}{ESP\ (\%)}$$

ESI values of less than 0.05 indicate that a Grey Vertosol used for cotton production in Australia is likely to be dispersive, but a number of additional factors also affect this relationship and as such, it is not universally applicable (McKenzie 1998).

Suite of accompanying cations

The cations accompanying Na on soil exchange sites also have a significant impact on the dispersion of sodic soils. Magnesium has been implicated in soil structural deterioration, enhancing dispersion when compared with Ca but contributing less to dispersion than Na (Rengasamy *et al.* 1986). Emerson and Chi (1977) demonstrated that the dispersion of an illite clay soil under conditions of high Na was greater in Mg dominated systems, than in Ca dominated systems. Curtin *et al.* (1994) obtained comparable results in a smectite clay soil but determined that 10 times as much exchangeable Mg as Na was required to disperse a Ca dominated illite. Dontsova and Norton (2002) also found that Mg was less effective in the flocculation of Na dominated clays than Ca.

Clay mineralogy

The clay mineralogy of a soil contributes to the degree of dispersion that occurs under the given conditions of ESP and EC. For example, illite clays require a higher electrolyte concentration to stabilize them at a given ESP value than smectite clays (McKenzie 1998). Soils with larger contributions of 2:1 expanding lattice phyllosilicate clays are also generally more dispersive than soils with smaller contributions of these clays (Speirs 2005). Thus, smectite clays require a higher electrolyte concentration to stabilize them at a given ESP value than kaolinite clays.

Organic matter

It is widely accepted that organic matter has a positive effect on the physical properties of soils. Different types of organic matter act at different scales within the soil structure, but their general effect is to bond the soil together (Nelson and Oades 1998). Organic matter however is less influential in the structural condition of heavy clay soils, such as Vertosols, due to their generally small organic matter contributions (<2%) (Hulugalle and Entwistle 1997; Hulugalle *et al.* 2001) and the dominance of shrink-swell behaviour in determining their physical structure (Hubble 1984). Sodic soils also generally have low organic matter contents, due to their relatively low productivity and associated organic matter inputs and their relatively high losses of organic matter in erosion and leaching events (Nelson and Oades 1998).

Although the effects of organic matter on the physical condition of sodic soils are variable, organic matter in sodic soils can generally contribute towards stabilizing aggregates, as in non-sodic soils (Quirk and Murray 1991). Barzegar (1997) found that organic matter had a positive effect on the stability of aggregates in Vertosols, irrespective of the ESP of the soil. Similarly, Yates (1972) found that soil organic matter was positively correlated with aggregate stability in Vertosols, but that the cation composition and EC of the soil was more important. Hulugalle and Finlay (2003) suggested that the ESI does not adequately describe the behaviour of soils in minimum tillage cotton production systems, due to the build-up of soil organic matter and microbial activity in these soils reducing their tendency towards dispersion.

pH

The pH of a soil has an impact on clay dispersion through its influence on the charge balance of variably charged clay sites. Increases in pH above 7 lead to an increase in the negative charge of variably charged minerals, which can exacerbate clay dispersion (Suarez *et al.* 1984). Thus, alkaline soil conditions aggravate dispersion in clay minerals that have significant contributions of variable charge, such as kaolinite, while the dispersion of clays dominated by permanent charge, such as smectite and illite, is less affected by pH.

1.2.3. *The implications of dispersion for sodic soils*

Dispersion has numerous adverse effects on the physical properties of sodic soils including reduced hydraulic conductivity, increased susceptibility to surface crusting and hard-setting, reduced water infiltration, increased runoff and soil erosion, reduced soil aeration and poor soil drainage.

Reduced hydraulic conductivity

The hydraulic conductivity (HC) of a soil is a measure of its ability to transmit water when exposed to a hydraulic gradient. The maintenance of stable soil aggregates is important in sustaining soil HC, as HC is largely dependant on the structure of the soil matrix. Macropores are primarily responsible for the transmission of water through a profile and the return of aerobic conditions after a watering event, while micropores are largely responsible for the storage of water within the soil profile (Quirk 1978).

Shainberg and Caiserman (1971) established that there is a significant negative correlation between soil ESP and HC, even at low sodicity levels and that a constant maximum reduction in HC is achieved at higher sodicity levels. The nature of this relationship is also highly dependant on the EC of the percolating solution and is influenced by all of the aforementioned factors; hence soil ESP alone does not predict the HC of soils (Quirk and Schoefield 1955). The primary mechanism responsible for the decreased permeability of sodic soils at low EC values is the swelling of clay domains (Quirk and Schoefield 1955). It remains unclear to what extent the blocking of soil pores upon clay dispersion contributes to reductions in the HC of sodic soils (Quirk 2001).

Reduced infiltration

Infiltration is the movement of water into the soil. The primary soil constraint to infiltration in many soils is the formation of a thin surface layer with higher strength, smaller pores and lower HC than the underlying soil (Bradford *et al.* 1987). The poor aggregate stability exhibited by sodic soils upon wetting contributes to this seal or crust formation and consequent reductions in infiltration rate (Kazman *et al.* 1983). Primarily, the swelling of aggregates decreases the size of soil surface pores and fine dispersed soil material may partially block soil pores. Hence, runoff of applied water or rainfall is increased where surface pores are sealed or reduced in size (Hillel 1980).

Soil strength

In the sodic Vertosols commonly utilized for cotton production, shrinkage during drying prevents the development of hard-set horizons but sodic clays are still more coarsely blocky that non-sodic clays (So and Aylmore 1993). Hard-setting reduces seedling emergence and early plant growth and although sodic Vertosols do not exhibit strict hard-setting behaviour, there is still a negative effect of sodicity in Vertosols on seedling performance (McKenzie *et al.* 1993).

The occurrence of slaking and dispersion throughout a sodic profile and consequent reductions in the size and distribution of soil pores has implications for the strength of sodic soils, resulting in an increase in soil bulk density (So and Cook 1993). The high strength of sodic soils can be significant in reducing plant root growth and thus access to nutrients (Cornish *et al.* 1984; Kuchenbuch *et al.* 1986).

Increased susceptibility to waterlogging

Crops produced on sodic soils frequently suffer aeration stress after irrigation or rainfall (Jayawardane and Chan 1994) as restricted infiltration of water results in waterlogging in the surface soil layers and restricted internal drainage results in waterlogging in sodic subsoils (McIntyre 1979; McIntyre *et al.* 1982). When a soil becomes waterlogged, the pore space in the soil structure that usually allows the exchange of gas between the soil and atmosphere is filled with water and diffusion of oxygen is severely reduced. Root and micro-organism respiration can then totally deplete the soil of oxygen within a 24 hr period and a loss of nitrate and build up of carbon dioxide and sometimes ethylene occurs (Trought and Drew 1980b). The consequences of waterlogging for the plant may include reduced or ceased growth, the death of root apices and changes to the patterns of nutrient accumulation (Trought and Drew 1980b; c; d).

Reduced plant available water

Plant Available Water Capacity (PAWC) is a phrase used to describe the amount of water present in a soil between field capacity and permanent wilting point. A negative correlation has been established between soil ESP and PAWC, under conditions of low EC. This has been attributed to the loss of porosity in the PAWC-range of sodic soils due to the processes of swelling and dispersion (Gardiner *et al.* 1984; McCown *et al.* 1976; McIntyre *et al.* 1982). Additionally, sodic soils often have low levels of macroporosity, which can restrict water intake during rainfall or irrigation. The resultant reduction in water storage can lead to the crop suffering premature water stress (McIntyre *et al.* 1982). Similarly, restricted root growth in sodic soils may result in lower plant rooting depth and a lower effective profile of available water.

The concept of a non-limiting water range (NLWR) was first proposed by Letey (1985). The NLWR is the water content range over which plant growth and development are not restricted by poor aeration in wet soil or hardness and water stress in dry soil. Da Silva and Kay (1987) proposed the idea of least-limiting water ranges (LLWR) because plant growth varies continuously according to water availability, aeration and soil strength. The LLWR is defined as the range of soil water content values after rapid drainage has ceased, within which limitations to plant growth associated with water potential, aeration and mechanical resistance to root penetration are minimal (da Silva *et al.* 1994).

In sodic soils, the LLWR can be very narrow, with crops suffering aeration stress after irrigation or rainfall and excessive soil strength and water stress becoming limiting early in the drying cycle (Jayawardane *et al.* 1987; Rengasamy 2002). With increasing soil sodicity, the strength of the soil increases and the LLWR becomes narrower, eventually coming to a point when the penetration resistance at the plastic limit is the same as the penetration resistance, at which cotton root growth is ceased (McKenzie and McBratney 2001). These factors can make it difficult for crop managers to maintain the soil water content within the LLWR throughout the growing season, with more frequent irrigations required and a greater risk of waterlogging occurring (Oster and Jayawardane 1998).

1.3. The chemical properties of sodic soils

Sodic soils are often associated with a number of chemical properties that affect the availability of nutrients to plants. These chemical properties include elevated pH, high soil solution Na concentrations, altered exchange equilibrium and changes in redox potential.

High pH

The Vertosols commonly used for cotton production in Australia tend to have alkaline pH values because they are often found in weakly leached environments (i.e. dry climates) (Isbell 1996). Soil alkalinity occurs as a result of the cumulative effects of long-term inputs of bases and outputs of acids. Alkaline anions such as bicarbonate, carbonate or hydroxide occur in the soils mainly as a result of removal of hydrogen ions from the soil, through the weathering of silicate minerals. If there is sufficient flushing of the profile with water containing dissolved CO_2, then alkaline bicarbonate salt weathering products are leached out of the soil profile and it will not become alkaline. The weakly leached soils of dry climates have little acid input, such as H_2CO_3 from rainfall, but may have inputs of bases from weathering of silicate minerals, and deposition of alkaline aeolian material (eg parna). Thus, in dry climates, alkalinity can accumulate and the soil pH rises.

Increases in soil pH with increasing soil sodicity occur in soils containing carbonates largely due to the displacement of adsorbed Ca and precipitation of carbonates with increasing soil Na concentrations (Guerrero-Alves *et al.* 2002). When the Na concentrations in a calcareous soil increase, adsorbed Ca is displaced, raising the soil solution Ca concentration. In turn, this process causes $CaCO_3$ to precipitate, lowering the carbonate concentration in solution and hence increasing the soil pH. It is also possible that the common causes of both sodicity and alkalinity contributes to the correlations between these soil properties in the field. For example, weak leaching combined with Na inputs via rainfall results both in increased soil exchangeable Na and high pH.

The contribution of the carbonate precipitation to the rise in pH of sodic soils can be determined using data collected by Cruz-Romero and Coleman (1975). Their data indicates that at ESP values between 0-100, the pH of montmorillonite clay without $CaCO_3$ present increased from 7.2 to 7.7 and the pH of montmorillonite clay with $CaCO_3$ present increased from 8.2 to 10.0. Hence the presence of $CaCO_3$ is necessary for large rises in pH, which in turn explains the presence of some neutral and acid sodic soils.

An additional influence on the pH of sodic soils is the level of salinity present. Following the dissociation of neutral salts (namely chlorides and sulfates) the cation concentration of the solution increases and the equilibrium shifts towards cation adsorption and H^+ desorption. Thus, soluble neutral salts moderate any pH increases in saline soils (Filep 1999).

Exchange equilibria

Sodic soils used for agricultural production have been reported to have soil solution Na concentrations of up to 131 mmol L^{-1} and SAR values of 50 (Naidu *et al.* 1996). High soil solution Na affects the availability of nutrients to plants due to changes in the ion exchange equilibria and solubility of some compounds. The exchangeable cations found in irrigated Vertosols consist largely of Ca and Mg, with a small proportion of K and variable proportion of Na. Irrigation water may also contain appreciable quantities of Na salts (USSL 1954). The equilibrium that exists between the cations in the soil solution and the cations on the exchange sites is constantly changing according to the moisture content of the soil (Russell 1973).

The relative distribution of the cations between the soil and solution phases occurs according to the Gapon equation. This equation can be outlined as follows, where $_c$ denotes exchangeable cation concentration in mmol kg-1, [ ] denotes solution cation concentrations in mmol L^{-1} and k is the Gapon selectivity coefficient;

$$\frac{Na_c}{Ca_c + Mg_c} = k\frac{[Na]}{\sqrt{[Ca]+[Mg]}}$$

This equation states that the ratio of the exchangeable Na ions to the exchangeable divalent ions, Ca^{2+} and Mg^{2+} is proportional to the ratio of the Na^{+} ion concentration in the soil solution to the square root of the total divalent ion concentration (Russell 1973). The implications of this for the chemistry of sodic soils, are that high concentrations of Na ions in the soil solution severely restrict the presence of divalent cations in the soil solution (Guerrero-Alves *et al.* 2002), which may in turn have implications for the availability of Ca and Mg to plants. Similarly, exchange equilibrium shifts have the potential to limit the availability of K to plants (Maathuis and Amtmann 1999).

Waterlogging and redox chemistry

Waterlogging is a prominent problem in sodic soils, as sodicity in the topsoil can result in low infiltration and surface waterlogging and subsoil sodicity can result in waterlogging in deeper horizons. Waterlogging can alter the availability of nutrients to plants, due to the chemical transformations of nutrient ions, brought about by changes in redox conditions.

When a soil is waterlogged, aerobic organisms reduce O_2 at a faster rate than it can diffuse through the soil and an anaerobic environment rich in CO_2 develops. Anaerobic bacteria then use oxidized soil components to replace O_2 as an electron acceptor (Russell 1973). Redox potential (E_h) is a quantitative measure of the tendency of a particular system to accept or lose electrons (Willett 1983). When a soil becomes waterlogged, there is a decline in E_h, as anaerobic bacteria use soil components as final electron acceptors in the place of O_2. The stability of a redox substance under the prevailing soil E_h is dependent on the standard potential (E_o) of its redox couple. Thus, when a soil becomes waterlogged, the oxidation-reduction reactions occur in a series (Russell 1973; Russell *et al.* 1988) The oxidation-reduction potentials of a typical soil system are illustrated in Table 1-1.

Table 1-1 The oxidation-reduction potentials of a typical soil system

Oxidation Reduction System	Oxidation Reduction Potential (V) @ 25°C	
	pH 5	pH 7
$O_2 + 4H^+ + 4e^- \Leftrightarrow 2H_2O$	9.3	8.2
$NO_3^- + 2H^+ + 2e^- \Leftrightarrow NO_2^- + H_2O$	5.3	4.2
$MnO_2 + 4H^+ + 2e^- \Leftrightarrow Mn^{2+} + 2H_2O$	6.4	4.1
$Fe(OH)_3 + 3H^+ + e^- \Leftrightarrow Fe^{2+} + 3H_2O$	1.7	-1.8
$SO_4^{2-} + 10H^+ + 8e^- \Leftrightarrow H_2S + 4H_2O$	-0.7	-2.2
$CO_2 + 8H^+ + 8e^- \Leftrightarrow CH_4 + 2H_2O$	-1.2	-2.4
$2H^+ + 2e^- \Leftrightarrow H_2$	-2.9	-4.1

(Russell 1973)

In field production situations, the nutrients most likely to become limiting to cotton growth following a waterlogging event are N, P and K (Hocking *et al.* 1985; 1987). The reduction of nitrate to nitrite and damage to active N uptake mechanisms contribute to N deficiency in cotton plant exposed to waterlogging, while damage to active P and K uptake mechanisms is largely responsible for the reductions in cotton P and K concentrations (Drew and Sisworo 1979; Trought and Drew 1980c). Waterlogging can also result in an increase in the concentrations of the plant available Mn^{2+} in the soil, due to the reduction of MnO_2. Potentially waterlogging could result in toxic accumulation of Mn by plants exposed to a period of waterlogging, but Mn toxicity has been reported in waterlogged cotton production situations (Hocking *et al.* 1987). Manganese toxicity is unlikely to limit cotton growth in sodic soils, as above pH 7, Mn availability has been found to decrease logarithmically, reaching a minimum value at pH 9 (Lindsay 1979).

1.4. Constraints to plant growth and nutrition in sodic soils

Constraints to plant production in sodic soils occur as a result of;

- Restricted root growth and impaired root function. This is caused by physical impediments to root growth and poor soil aeration.
- The altered composition of the soil solution. This includes chemical transformations and equilibrium shifts induced by changes in soil redox potential, pH, and Na concentration.

1.4.1. *Physical impediments to root growth and nutrient access*

The physical properties of sodic soils are considered to be the primary limitations to their productivity (Curtin and Naidu 1998). The soil physical properties that directly affect plant growth are soil strength, aeration and water supply (Letey 1985).

<u>Soil strength</u>

High soil strength in sodic soils can have a negative effect on root growth and thus the ability of plants to access nutrients. Root elongation decreases with increasing soil strength due to the force required to displace soil particles (Clark *et al.* 2003). Root cell division and elongation is also decreased in situations of mechanical impedance and the diameter of the root adjacent to the apex generally increases (Atwell 1988). This increase in root diameter is due to cortical cells enlarging radially rather than axially (Clark *et al.* 2003) and as a result, the cortical cells of roots grown in soils of high strength are generally shorter and fatter than those grown in loose soil (Croser *et al.* 2000). Chassot and Richner (2002) reported that an increase in soil strength decreases root length, root mass, and root/shoot ratio, increases in root diameter and concentrates roots higher up the profile.

The penetration resistance at which cotton growth ceases has been estimated at 1490 kPa and the penetration resistance corresponding to a 50% reduction in root growth is approximately 600 kPa (McKenzie and McBratney 2001). Reductions in cotton root growth have been correlated with reductions in nutrient uptake, especially P, and decreases in dry matter and lint yield (Rosolem *et al.* 1998).

The thicker roots caused by high soil strength are less efficient in acquiring water and nutrients compared to plants having thinner roots because the total length of the root system of a given mass is lower with thicker than with thinner roots, which leads to smaller volumes of soil explored (Eissenstat 1992). The amount of K and P taken up by a plant is dependant upon the rate of K taken up per unit of root length and the total root length (Cornish *et al.* 1984; Kuchenbuch *et al.* 1986). The mobility of these nutrients increases with increasing soil moisture due to a decrease in the tortuosity of the diffusion path with increased soil moisture. Thus, K and P influx per unit length of root is slightly increased with increasing soil bulk density, because the volumetric water content of the soil is greater at a given gravimetric water content (Cornish *et al.* 1984; Kuchenbuch *et al.* 1986). The total amount of K and P taken up by plants decreases in soils of high strength however, due to reduced root length and root hair production and the consequently diminished root exploration of the soil volume (Cornish *et al.* 1984; Kuchenbuch *et al.* 1986).

<u>Aeration</u>

Another implication of sodicity may be an increase in the incidence of soil waterlogging events, due to a dispersion induced decrease in soil hydraulic conductivity (Shainberg and Caiserman 1971). The aeration stress placed upon plants under waterlogged conditions can have a major effect on both shoot and root growth (Marschner 1995), which in turn places limitations on the ability of the plant to access nutrients (Singh *et al.* 2002). The air-filled porosity value at which oxygen diffusion becomes limiting to cotton production in a Grey Vertosol is approximately $0.128 m^3/m^3$ (or 13% by volume) (Hulme 1987).

Plants grown under aerobic conditions actively accumulate K and P and partially exclude Na over a wide range of Na concentrations. Under anoxic conditions however, uptake of P and K is severely reduced and increased levels of Na accumulate in plant tissues as membrane selectivity for P and K uptake and Na exclusion are compromised by root anoxia, due to a rapid decline in root adenosine triphosphate (ATP) levels (Drew and Dikumwin 1985; Drew and Lauchli 1985). Extended periods of anoxia also reduce root cell membrane integrity and thus ions pass through non-selectively (Trought and Drew 1980b); which can lead to a loss of K from root tissues and increased accumulation of Na (Wiengweera and Greenway 2004). McLeod (2001) observed that waterlogging during the peak flower and boll-filling period of cotton resulted in reduced uptake of K and P, the relocation of K and P from the leaves to the fruit and the development K and P deficiency symptoms in the leaves and petioles.

Water availability

The instability and low macroporosity of sodic soils restricts the intake of water during irrigation and rainfall events and may increase the amount of water lost through evaporation and runoff (Loveday *et al.* 1970). The resultant reduction in water storage can lead to crops suffering from water stress during the soil drying cycle in dryland agriculture (McIntyre *et al.* 1982) and to reduced irrigation efficiencies in irrigated agriculture (Jayawardane and Chan 1994). Additionally, the NLWR in sodic soils can be very narrow, with crops suffering aeration stress after irrigation or rainfall and excessive soil strength and water stress becoming limiting early in the drying cycle (Jayawardane *et al.* 1987; Rengasamy 2002). These factors can make it difficult for crop managers to maintain the soil water content within the NLWR throughout the growing season (Oster and Jayawardane 1998). The formation of a surface seal can also reduce the establishment of seedlings and limit their early growth (So and Cook 1987).

1.4.2. *Chemical limitations to plant growth and nutrition in sodic soils*

Nutrient deficiencies and toxicities are common in sodic soils and are caused by changes in soil redox potential, high pH and elevated Na in the soil solution. While nutrient deficiencies and toxicities in plants grown on sodic soils are situation specific, commonly encountered fertility problems in sodic soils include deficiencies in micronutrients such as Zn, Fe and Mn and toxicities in Na and B.

High sodium concentrations

Sodic soils are characterised by high soil solution concentrations of Na (Naidu *et al.* 1995). High concentrations of Na have been reported to be toxic to plants (Maas and Hoffman 1977), although specific plant and soil concentrations at which Na toxicity limits plant growth is difficult to establish with certainty due to the confounding of the effects of high levels of soil solution Na with other factors, including poor soil physical condition and salinity.

Apart from the direct effects of Na on plant growth, Na-induced cation imbalances in plant tissues have also been reported. Carter (1979) reported that if the ratio of Ca to total cation concentration (TCC) ratio, in the soil solution is <0.15 (mM), impaired uptake of Ca can result in plant Ca deficiency in barley. Although the critical soil solution Ca:TCC resulting in plant Ca deficiency can vary between individual plant species and genotypes (Grattan and Grieve 1992). Adequate plant concentrations of Ca are necessary to maintain normal membrane stability and function (Cramer *et al.* 1985). Under conditions of high Na and low Ca in solution, Na displaces Ca from the plasma membrane of root cells, which can result in K leaking from the root tissue (Cramer *et al.* 1985).

Nitrogen loss

The increased frequency and/or severity of waterlogging events associated with soil sodicity have direct implications for the availability of nutrients to cotton crops. Waterlogging directly reduces the accumulation of N by the crop and the denitrification of soil N means that even after the waterlogging has ceased, there may be less N available for the crop (Rao and Batra 1983; Rochester *et al.* 1991).

Micronutrient deficiencies

Micronutrient deficiencies in sodic soils are commonly associated with elevated soil pH values and anaerobic redox environments. In addition, factors, such as organic matter content, clay mineralogy and other accompanying elements are also important in controlling micronutrient availability.

The availability of both Zn and Cu in soil are largely controlled by pH, with the solution concentrations of these nutrients decreasing with increasing pH, due to precipitation and sorption reactions (Hodgson *et al.* 1966). The solubility of Zn and Cu are increased in waterlogged conditions, however the pH effects are dominant in alkaline soils (Naidu and Rengasamy 1993). Additionally, Zn availability in sodic soils is further reduced, due to the kinetics of Na-Zn exchange. Calcium competes more effectively for colloidal exchange sites than Zn, but Zn competes more effectively than Na for colloidal exchange sites. Thus there is a tendency for Zn to be largely present on exchange sites in sodic soils and thus less available to the plant (Shukla *et al.* 1980).

The availability of Fe and Mn are also significantly reduced under conditions of high soil pH, with the concentrations of the plant available forms of these nutrients (Fe^{2+} and Mn^{2+}) decreasing logarithmically with increasing pH and reaching a minimum at approximately 9 (Lindsay 1979). Soil redox potential also plays a significant role in determining the status of these nutrients in irrigated Vertosols however, with the soil solution concentrations of Mn^{2+}

and Fe^{2+} increasing with decreasing soil redox potential (Ponnamperuma 1972). Manganese and Fe toxicity are not generally reported in sodic Vertosols (Hocking *et al.* 1987), due to the negative effects that elevated soil pH has on Mn and Fe availability (Ponnamperuma 1984). Additionally, although plants subjected to waterlogging may contain increased concentrations of Fe, due to an increase in the soil concentrations of plant-available Fe^{2+}, most of this cannot be used by the plant. The build-up of CO_2 in waterlogged soils results in the formation of bicarbonate ions, which in turn increases the concentration of bicarbonate in the leaf tissues. Under these conditions, Fe becomes unavailable for use in plant tissue, as Fe^{2+} is converted to Fe^{3+} and symptoms of chlorosis appear (Chen and Barak 1982).

<u>Boron toxicity</u>

Soil solution B concentrations are determined by adsorption and precipitation reactions and these are controlled by pH, exchangeable cations, ionic strength and soil water content (Curtin and Naidu 1998). Increasing pH enhances adsorption of B onto clay minerals due to changes in soil solution B speciation. With pH values >9 however, hydroxide ions compete with B for adsorption sites and there is a decrease in B adsorption (Hingston 1964). Additionally, at pH values >8, the adsorption of B onto clay minerals is reduced by soil solution Na and increased by soil solution Ca (Keren and Gast 1981). The low adsorption of B onto clay minerals in the presence of Na and soil pH values >9, has the potential to induce B toxicities in some sodic soils (Cartwright *et al.* 1986; Holloway and Alston 1992).

<u>Phosphorus availability</u>

Phosphorus tends to be more available to plants in sodic than in non-sodic soils, due to their elevated Na concentrations and susceptibility to waterlogging events (Curtin *et al.* 1992a). Waterlogging tends to increase soil solution concentrations of P, through the reduction of Fe^{3+} phosphate to the more soluble Fe^{2+} phosphate (Ponnamperuma 1984). In sodic soils, Na concentration is more influential in controlling P availability than redox potential (Willett and Cunningham 1983), with soil solution P concentrations increasing with increasing soil sodicity due to the dissolution of Ca-P compounds and the release of sorbed P with increasing clay surface negative potential (Curtin *et al.* 1992a; Gupta *et al.* 1990). Despite this increase in P availability, P deficiency is commonly reported in crop plants produced on sodic soils (Curtin and Naidu 1998; Naidu and Rengasamy 1993) Although the mechanisms behind these deficiencies are not fully understood, it is likely that restricted root growth is a factor (Cornish *et al.* 1984)

1.5. Sodicity-nutrition research

The effects of sodicity on the physical and chemical characteristics of soils have been well characterised. The limiting effects of sodic soils on the growth and nutrition of crops, that occur both directly as a result of the increasing concentration of Na and indirectly as a result of the physical limitations, are less clear and more difficult to quantify. There exists a vast body of literature in which field, soil and nutrient based culture systems have been used to try to quantify the impacts of elevated Na concentrations on plant nutrition. The results of these studies vary significantly however, due to the variety of factors that contribute to the physical and chemical condition of a soil at a given ESP value, species and varietal differences in plant response to sodicity and the frequent confounding of salinity and/or poor soil physical condition with direct effects of elevated levels of soil Na on plant growth and nutrition.

1.5.1. *Soil and nutrient culture systems*

Soil culture systems

Numerous authors have explored the effects of sodicity on plant nutrition in the glasshouse through the addition of Na salts to soil pot culture systems (e.g. $NaHCO_3$ or NaCl). The consistent outcomes of this type of experimentation have been that increases in soil sodicity result in declining plant growth, reductions in plant tissue K and Ca concentrations and increases in plant tissue Na concentrations. Prasad *et al.* (2003) observed that as soil ESP increased, there was a corresponding increase in the shoot Na concentrations and decrease in the shoot Ca and K concentrations of four mint varieties. Bernstein and Pearson (1956), Bains and Fireman (1964) and Pearson and Bernstein (1956) also observed negative correlations between the growth of a variety of crop plants and soil ESP. As soil ESP increased, the Na content of the crop plants generally increased and the crop K and Ca contents generally decreased, although considerable differences existed between the various crop species. Chang and Dregne (1955) observed reductions in cotton and alfalfa growth at an ESP of 29%. Wright and Raiper (2000) also measured correlations between increasing soil sodicity and increasing levels of Na, decreasing K/Na ratios and decreasing Ca concentrations in wheat. As the soil ESP increased, there was also a corresponding decrease in plant height, leaf area and straw and grain yield.

The methodologies used in these soil culture systems have limitations however, as the addition of Na salts increases soil salinity, unless the excess salt is leached from the soil, confounding salinity with sodicity. This is especially true for the high Na applications required to create a strongly sodic clay soil (ESP >15%). For example, Wright and Raiper (2000) used $NaHCO_3$ salt to sodify a clay loam, raising the ESP from 1 to 38% but also increasing the EC_{se} from 1.8 to 6.1. The precipitation of carbonates is also largely responsible for the high pH values commonly found in calcareous sodic soils (Cruz-Romero and Coleman 1975). Thus, using carbonate salts to vary soil sodicity can increase the soil pH to excessive levels and confound sodicity with artificial extremes of pH. For example, in the above-mentioned experiment conducted by Wright and Raiper (2000) the increase in ESP from 1 to 38% was also associated with an increase in pH (1:5 H_2O) from 6.3 to 8.7.

<u>Nutrient solution systems</u>

Numerous authors have explored the impacts of sodicity on plant nutrition in the glasshouse through the use of nutrient solution experiments. Maas and Grieve (1987) grew corn in a nutrient solution, with the addition of iso-osmotic concentrations of NaCl and $CaCl_2$ and it was observed that Na had a negative effect on plant growth and the uptake of Ca at Ca/Na ratios less than 5.7. Aslam *et al.* (2003) used nutrient solutions with 100 mM NaCl and varying concentrations of Ca to grow safflowers and observed that increasing solution concentrations of Ca decreased plant uptake of Na and that solution Na decreased the uptake of K. Al-Ani and Ouda (1972) used nutrient solutions and sand culture with the addition of various levels of Na and K to grow bean plants. Sodium increased the K concentration in the shoots and decreased K concentration in the roots but had no effect on plant Ca concentrations. Additionally, Na was retained in the roots, so the Na concentration in the shoots was unrelated to its concentration in the growth medium.

Solution culture experiments are useful in the study of interactions between sodicity and plant growth and nutrition because they effectively enable sodic soil solution chemistry to be separated from poor soil physical condition. This methodology also has limitations however, which are largely related to difficulties of their design and application to practical situations. Firstly, it is difficult to change the concentration of a nutrient in the solution without also altering either the osmotic potential or the concentration of another nutrient confounding both. Secondly, it is difficult to conduct nutrient culture experiments at concentrations that mirror those in the soil, especially for nutrients that occur in low concentrations in the soil solution, such as K and P. Thus relationships, which may arise in the high nutrient concentrations of a nutrient culture system, may not be apparent under soil conditions and vice versa.

1.5.2. *Mechanisms of sodium toxicity to plants*

With basic soil and solution culture experiments highlighting that Na has an effect on the patterns of growth and nutrient accumulation in a variety of plant species experiments have also been conducted in order to determine the mechanisms of these effects. This issue has largely been addressed in the context of the effects of NaCl salinity on nutrient uptake, but such results are relevant to studies of sodicity when steps are taken to isolate the direct effects of Na from the effects of osmotic potential and chloride.

Plant growth is reduced by NaCl salinity and it has been established that there are two broad reasons for this. The increased osmotic pressure associated with elevated concentrations of NaCl in the growth medium reduces plant growth. Through the use of iso-osmotic concentrations of mannitol however, it has been established that there is an additional component to this growth reduction, that is specific to Na (Cramer *et al.* 1985; Kinraide 1999).

The effects of NaCl on plant growth are apparent at a number of different levels. At the molecular level, NaCl stress is manifested in reduced binding of Ca to the plant plasma membranes (Yermiyahu *et al.* 1994). At the whole plant level NaCl stress is manifested in reduced root (Kent and Lauchli 1985; Kurth *et al.* 1986; Zhong and Lauchli 1993), reduced shoot growth (Cramer 1992; Cramer *et al.* 1989; Yeo *et al.* 1991) and changes in ionic composition of the plant (Ben-Hayyim *et al.* 1987; Nakamura *et al.* 1990; Reid and Smith 2000). Sodium chloride salinity also affects the nature of root development, by altering the Na/Ca ratio of the growth medium. Kurth *et al.* (1986) and Huang and Redman (1995) found that roots grown in high Na and low Ca mediums are shorter and thicker than those grown in standard media. The Na/Ca ratio of the growth medium also has an effect on the development of root hairs, reducing their length and density (Shabala *et al.* 2003).

A consistent feature of this body of experimentation is the ameliorative effect of increasing the concentration of Ca in the growth medium. The addition of Ca to a solution containing NaCl improves root elongation (Kent and Lauchli 1985; Kurth *et al.* 1986) and shoot growth (Cramer 1992; Cramer *et al.* 1989; Yeo *et al.* 1991), prevents symptoms of Ca deficiency (Maas and Grieve 1987), reduces root thickening (Kurth *et al.* 1986) and restores the growth and development of root hairs (Shabala *et al.* 2003). At high salinities however, much of the growth inhibition by NaCl can be attributed to osmotic effects and these occur independently of the Ca concentration of the growth medium (Cramer *et al.* 1989). Kinraide (1999) found that the negative effect of NaCl salinity on wheat roots could be restored by the addition of Ca if the concentration was <130 mM. Additions of solute beyond this level reduced root elongation regardless of the concentration of Ca, indicating the effects of osmotic stress beyond this point.

The ionic component of NaCl stress is related to decreasing levels of Ca activity at the plasma membrane of the plant roots. As the concentration of Na in the growth medium increases, there is a corresponding decrease in the activity of Ca in the growth medium (Cramer and Lauchli 1986; Shabala *et al.* 2003). Thus, concentrations of Ca that are adequate for growth in low Na mediums may not be adequate in high Na mediums (Cramer and Lauchli 1986; Cramer *et al.* 1986). The amelioration of Na toxicity by Ca involves increasing the activity of Ca in the solution (Reid and Smith 2000).

The ameliorative effects of increasing levels of Ca activity at the plasma membrane on plant growth in solutions affected by NaCl salinity have been attributed to a number of different processes, independent of osmotic stress. These processes include;

- Restoration of K uptake selectivity at the plasma membrane by Ca (Epstein 1961; LaHaye and Epstein 1969; Lynch and Lauchli 1985)
- Increased binding of Ca to the plasma membrane, stabilization of membrane structure by Ca (Pooviah and Reddy 1987) and thus reductions in K leakage and Na influx at the plasma membrane (Cramer and Lauchli 1986; Cramer *et al.* 1985; Cramer *et al.* 1987)
- Restoration of Ca and K xylem transport (Lynch and Lauchli 1985)
- Positive effects of Ca on Na and K compartmentalisation within plant cells (Kinraide 1999; Lauchli 1990).

The relative importance of each of these processes in sodic soils remains unclear and may differ according to the species concerned or nature of the Na stress imposed on the plant. Each of these processes will be discussed in further detail below.

Maintenance of potassium uptake selectivity at the plasma membrane

The existence of a relationship between the Na content of the growth medium and the K content of plant shoots and roots was determined initially in bean and barley plants by Epstein (1966). Early work suggested that K and Na uptake occurred via dual mechanisms in the plasma membrane, one of high K affinity and one of low K affinity. Sodium was considered to compete effectively with K for uptake at the low K affinity mechanism but the high K affinity mechanism was considered to be highly selective for K (Epstein 1966). The positive affect of Ca on plant growth and ionic composition under conditions of high Na was attributed to the maintenance of selectivity of the high K affinity mechanism (Epstein 1961).

The ability to differentiate between K influx and K efflux led Cramer *et al.* (1985) to determine that the use of supplemental Ca on cotton grown under high NaCl conditions has no direct effect on K influx. The beneficial effect of Ca under these conditions was instead attributed to the maintenance of the integrity of the membrane and thus the prevention of K leakage from the root cells. The factor most significantly correlated with the increasing influx of K into the cotton plants grown in various NaCl solution concentrations, is increasing root weight (Cramer *et al.* 1987). Kurth *et al.* (1986) determined that the presence of Ca increases cell length and division in saline soils and thus Ca is indirectly important in the maintenance of K influx in saline soils through the maintenance of root growth.

Increased binding of calcium to the plasma membrane

Calcium has a role the promotion of cell wall development and the maintenance of structure in the plasma membrane (Hanson 1984; Pooviah and Reddy 1987). Removal of Ca from the plasma membrane of a cell by EDTA results in leakage of K from the cell (Weimberg *et al.* 1983). Similar results have also been obtained under conditions of high Na in the growth medium (Ben-Hayyim *et al.* 1987; Cramer *et al.* 1985; Nakamura *et al.* 1990; Yermiyahu *et al.* 1994).

Yermiyahu *et al.* (1997) measured the effect of various concentrations of Na and Ca on the binding of Ca to the plasma membrane of melons and the consequent level of root elongation. A correlation was observed between the salt-tolerance of melons and the extent of Ca binding to the plasma membrane, with the more salt tolerant melon variety having a lower critical Ca binding percentage at which optimal root growth occurred. The role of Na displacement of Ca from the plasma membrane in NaCl toxicity has also been established through the analysis of the growth of wheat seedlings in solutions of varying Na, Ca and K concentrations (Kinraide 1998).

Sodium-induced depletion of K from plant tissue has been cited as a mechanism for NaCl toxicity by a range of authors (Ben-Hayyim *et al.* 1987; Cramer *et al.* 1985; Nakamura *et al.* 1990; Yermiyahu *et al.* 1997). The difficulty in determining the role of Na-induced K deficiency in NaCl toxicity occurs in trying to establish a causal relationship from a variable that may be confounded. Kinraide (1999) used 30 solutions of varying concentrations of Ca, Na and K in order to try and determine the existence or not of such a relationship in wheat seedlings. No Na-induced reduction in root or shoot K concentration was discovered, contradicting the K depletion hypothesis. Additionally, root and shoot elongation was found to occur at optimal levels at low K concentrations in both roots and shoots. These results contradict those observed in a variety of other experiments. For example, Shabala *et al.* (2003) found that critical levels for K deficiency were reached in barley seedlings cultivated under conditions of NaCl salinity over a period of several days, due to K efflux from roots. It is important to consider that the experiment undertaken by Kinraide (1999) was short-term, with 2 day old wheat seedlings being grown for only 2 days. In larger plants grown over a longer period, such as those cultivated under a field situation, the loss of K from plant roots could result in deficiency.

Excessive Na influx into plant tissues has also been cited as a mechanism for NaCl toxicity by a number of authors (Cramer *et al.* 1987; Reid and Smith 2000; Yermiyahu *et al.* 1997).

Increased tissue concentrations of Na have been found in plant roots and shoots under increasing levels of NaCl (Kinraide 1999; Reid and Smith 2000) and increasing Na influxes measured under conditions of NaCl salinity (Yermiyahu *et al.* 1997). Again, the difficulty in determining the role of Na influx in NaCl toxicity occurs in trying to establish a causal relationship between Na and plant growth reductions when Cl also has the potential to reduce plant growth. A reduction in Na influx has been observed on numerous occasions with the addition of Ca to a high NaCl medium (Cramer *et al.* 1987; Kinraide 1999; Reid and Smith 2000; Yermiyahu *et al.* 1997). This would lend support to the hypothesis that Na influx is related to NaCl toxicity under conditions of low Ca. Kinraide (1999) however found that high Na concentrations in plant shoots reduce plant growth due to osmotic effects, but that there was no direct effect of high root Na concentrations on plant growth. Again, this experiment was only conducted using 2-day-old wheat seedlings for 2 days. Over a longer period of time, high root or shoot Na concentrations might reduce plant growth.

Restoration of calcium and potassium transport

Lynch and Lauchli (1985) hypothesized that Na toxicity may be due to a deficiency in Ca, induced by the inhibition of Ca transport from root to shoot. Reid and Smith (2000) however found no correlation between wheat shoot Ca content and growth, at constant Ca activity, with Ca transport from root to shoot being constant at both high and low NaCl concentrations. Reid and Smith (2000) also hypothesized that Na toxicity may be due to deficiencies in K, induced by the inhibition of K transport to the shoot but later observed no correlation between Na and K shoot concentrations and the growth of wheat. Kinraide (1999) also found that wheat growth was correlated to root K concentration and not shoot K concentration, indicating that the issue is not one of reduced K transport to the shoot.

Compartmentalisation

The ability of plants to maintain high cytosolic Na/K ratios within their cells is also an important element in salinity tolerance (Yeo 1998). A possible mechanism for the ameliorative effects of Ca on NaCl toxicity in plants is that it may allow more effective compartmentalisation of Na and K within plant tissue. Lynch and Lauchli (1988) and Lynch *et al.* (1989) demonstrated that NaCl increases cytoplasmic Ca. Using this information, Lauchli (1990) created a model for the role of Ca in the regulation of plant responses to high Na concentrations. He suggests that displacement of Ca at the plasma membrane by Na is sensed by a receptor in the membrane, which then activates the release of Ca from intracellular pools. This in turn may trigger changes in gene expression, metabolism, growth and development. It is possible that Ca in the cytosol ameliorates NaCl stress by increasing the efficacy of vacuolar Na compartmentalisation, allowing the maintenance of cytosolic K/Na ratios.

1.5.3. *Sodium tolerance mechanisms in cotton*

Numerous authors have studied the patterns of nutrient accumulation in cotton plants affected by NaCl salinity and significant variation exists in the salinity tolerance mechanisms of different cotton varieties. Lauchli and Stelter (1982) observed that salinity tolerance of cotton is related to the accumulation of Na and Cl in the shoot. In contrast, Rathert (1982) and Gorham and Young (1996) found that in Pima cotton (*Gossypium barbadense* L.) and some wild cotton varieties, Na accumulation in the shoot was related to salinity sensitivity. Studies undertaken by Leidi and Saiz (1997) found a positive correlation between Na accumulation and salinity tolerance in two cotton varieties and also noted that both the salinity sensitive and salinity tolerant species had increasing K/Na concentration ratios up the plant, indicating efficient translocation mechanisms of K through the plant. Ashraf and Ahmad (2000) found no difference in Na uptake between salt sensitive and salt tolerant cotton lines but correlated salt tolerance with increasing concentration of K and Ca in the leaves. Qadir and Shams (1997) also correlated cotton salt tolerance with improved K/Na ratios in the leaves.

The response of different plants to levels of Na in the soil can be broken broadly into two groups – Na-includers and Na-excluders. These two strategies are not mutually exclusive however and decreased uptake of Na by the roots may work in parallel with increased sequestration of Na in the shoots (Maser *et al.* 2002). The majority of halophytes are predominantly Na-includers, which means that they take up large amounts of Na and sequester it into the vacuoles of shoot and root cells. Glycophytes are predominantly Na-excluders, and exhibit an inverse relationship between Na uptake and salt tolerance (Marschner 1995). The balance between Na-inclusion and Na-exclusion mechanisms of Na tolerance differ between the various cotton varieties, although it appears that commonly cultivated modern varieties tend towards inclusion (Lauchli and Stelter 1982; Leidi and Saiz 1997). In contrast, salt-sensitive varieties of wheat tend towards Na-exclusion, transporting more Na to their shoots than salt-tolerant types (Joshi *et al.* 1980; Schachtman *et al.* 1989).

The ability of plants to maintain high cytosolic Na/K ratios within their cells has been found to be an important element in salinity tolerance (Yeo 1998). This suggests that it may be more relevant to measure the Na/K ratios within individual cells, rather than the Na/K ratios of whole plants or plant tissues when trying to quantify the level of salinity tolerance possessed by a plant. More consistent results in the correlations between Na and K uptake and salinity tolerance could possibly have been achieved if cytosolic Na/K ratios were also measured in the above studies.

1.6. Conclusions and further research

This review has identified the soil chemical, soil physical and plant factors that may contribute to the patterns of growth and nutrient accumulation that occur in cotton crops grown in sodic soils. The following chapters investigate the relative importance of these factors in cotton production systems in sodic Grey Vertosols.

This review has illustrated that the physical and chemical responses of soil to a particular level of soil sodicity depend upon a variety of other soil characteristics. This review has also highlighted that several plant factors contribute to Na toxicity in cotton and that the importance of these will vary with cotton variety and the time-scale over which the interaction is studied. Given the complexity of the plant-soil interactions that control the growth and nutrient accumulation of cotton in sodic soils, it is impossible to definitively quantify the relationship between soil ESP and cotton performance. The following experiments however aim to characterize the relative contributions of the various soil chemical, soil physical and plant factors to the patterns of growth and nutrient accumulation of modern Australian cotton varieties in Grey Vertosols, over the length of a cotton production season. While not directly applicable to each individual sodic soil and cotton variety, the results of these experiments can be used by cotton growers to assess the likely effects of sodicity on their production system and the principal mechanisms behind these effects. An understanding of these factors is important to allow cotton growers to assess the limitations placed on their farming system by sodic soils and to allow them to implement effective crop and soil management strategies in sodic cotton fields.

Chapter 2. Determining the effects of sodicity on the growth and nutrition of cotton produced in field situations

2.1. Introduction

Approximately 23% of the Australian landmass (NLWRA 2002) and 80% of the irrigated agricultural area in Australia is occupied by sodic soils (Rengasamy and Olsson 1993). Rengasamy (2001) estimated that more than 50% of soils used for high value crops such as cotton are affected by sodicity. Despite the prevalence of sodic soils in cotton farming systems however, the effects of sodicity on the growth and nutrition of cotton crops are poorly understood.

In a series of field experiments, at 30 different sites spread across a range of the cotton producing regions of eastern Australia and several growing seasons, Rochester (Unpublished) established the general relationships that exist between soil sodicity and nutrient accumulation in cotton crops. According to Rochester (Unpublished) cotton crops produced on sodic soils have higher leaf Na concentrations and lower leaf P and K concentrations than cotton crops produced on non-sodic soils and accumulate less dry matter, lint and total P, K and Ca. The extensive nature of this research and its repetition across a number of growing seasons adds confidence and broad relevance to the results. The significant variability of the results however, indicates that a variety of factors that are individual to each site contribute to the patterns of growth and nutrient accumulation in cotton crops.

In order to better understand the productivity and nutrition of cotton crops produced in sodic soils, an experiment was designed to minimise the variability associated with field research. The aim of this experiment was not to determine direct causal relationships between soil properties and plant performance. Rather, this experiment was designed as a tool by which to illustrate the type of nutritional and crop performance issues that occur in cotton crops produced in sodic soils, in conjunction with the earlier work carried out by Rochester (Unpublished). The cotton crop nutrient status and performance were monitored at sites with a range of sodicity levels within one field, in order that the experimental variation due to management and climate were largely eliminated. Confounding variations were still apparent however, between the different soil profiles utilised within this field. Comparisons of the data from this experiment and those carried out by Rochester (Unpublished) were used to inform the aims and methodologies of the subsequent glasshouse experiments, which were designed to determine the mechanisms responsible for the patterns of crop growth and nutrient accumulation measured in sodic cotton production systems.

2.2. Methods

2.2.1. *Experimental sites*

This experiment was conducted in a field on a commercial cotton property located approximately 30 km west of Moree, NSW (149.6°E, 29.5°S). This field had been used predominantly for irrigated cotton and dryland wheat cropping for approximately 25 years. Six sites were chosen in this field by assessing the results of a survey of bulk soil electrical conductivity, generated by an electromagnetic (EM 38) survey (Figure 2-1) and the results of an early season plant cell density index analysis, generated by an airborne digital multi-spectral imagery (DMSI) survey (Figure 2-2). Precision Cropping Technologies Pty Ltd in Narrabri, NSW, carried out both of these surveys. The EM 38 survey was carried out on 24 m transects, 20 cm above the soil hill planting hill surface, 7 days after a flood irrigation event, in the September immediately prior to the planting of the crop. Electromagnetic 38 surveys measure the average electrical conductivity of the soil to a depth of 1.5 m. The electrical conductivity of the soil is affected by its clay content, clay mineralogy, soil moisture, solution electrical conductivity and temperature (Johnson *et al.* 2003). Electromagnetic surveys can be used to infer spatial variation in soil type when combined with soil analysis (Ryan *et al.* 2001). The DMSI survey was carried out in January 2003, in the mid to late part of the cotton production season prior to the experiment. Digital multi-spectral imagery sensors collect data in 4 wavebands, corresponding to the infrared, red, green and blue wavelengths. These are mathematically combined to give a single value of the ratio of infra-red to red reflectance – the plant cell density index (Rampart and Abuzar 2004). Digital multi-spectral imagery surveys can be used to identify crop areas differing in plant productivity and vigour, although they do not necessarily correspond to the final crop yield (Rampart and Abuzar 2004). In this experiment, data from the EM 38 and DMSI surveys were visually combined to select specific sites for soil analysis. Soil analysis revealed that the specific sites had a range of sodicity levels and these were then used in the plant-sampling program.

At each site soil was sampled to a depth of 60 cm in 0-30 cm and 30-60 cm increments. A soil sampling depth of 60 cm was considered adequate for this experiment, as approximately 80% of cotton roots occur within 45 cm of the soil surface in furrow irrigated Grey Vertosols (Hodgson *et al.* 1990). One core was taken from each of the four plots at every site and bulked together for analysis. Significant variation in soil properties existed between the different sites and selected properties of these soils are presented in Table 2-1.

A commercial cotton crop (cv Sicot 289BR, CSD Pty Ltd) was planted in this field on the 6th October 2003, when the soil temperature was 18°C. Uniform management practices were applied across the whole area of the field throughout the season. In August 2003, 180 kg/ha of N was applied to the field as anhydrous ammonia. A further 80 kg/ha of N was spread as urea during the early fruiting period, just prior to an irrigation event. At planting 20 kg/ha of P was applied as $NH_4H_2PO_4$ (mono-ammonium phosphate) and 2 kg/ha of Zn was applied as $ZnSO_4$. The field was furrow irrigated and early weed control was carried out through inter-row cultivation. A variety of chemical pest control products were applied throughout the season.

Figure 2-1 Electromagnetic 38 survey of the experimental field, located at Moreton Plains, Moree. Sampling sites are indicated by black squares.

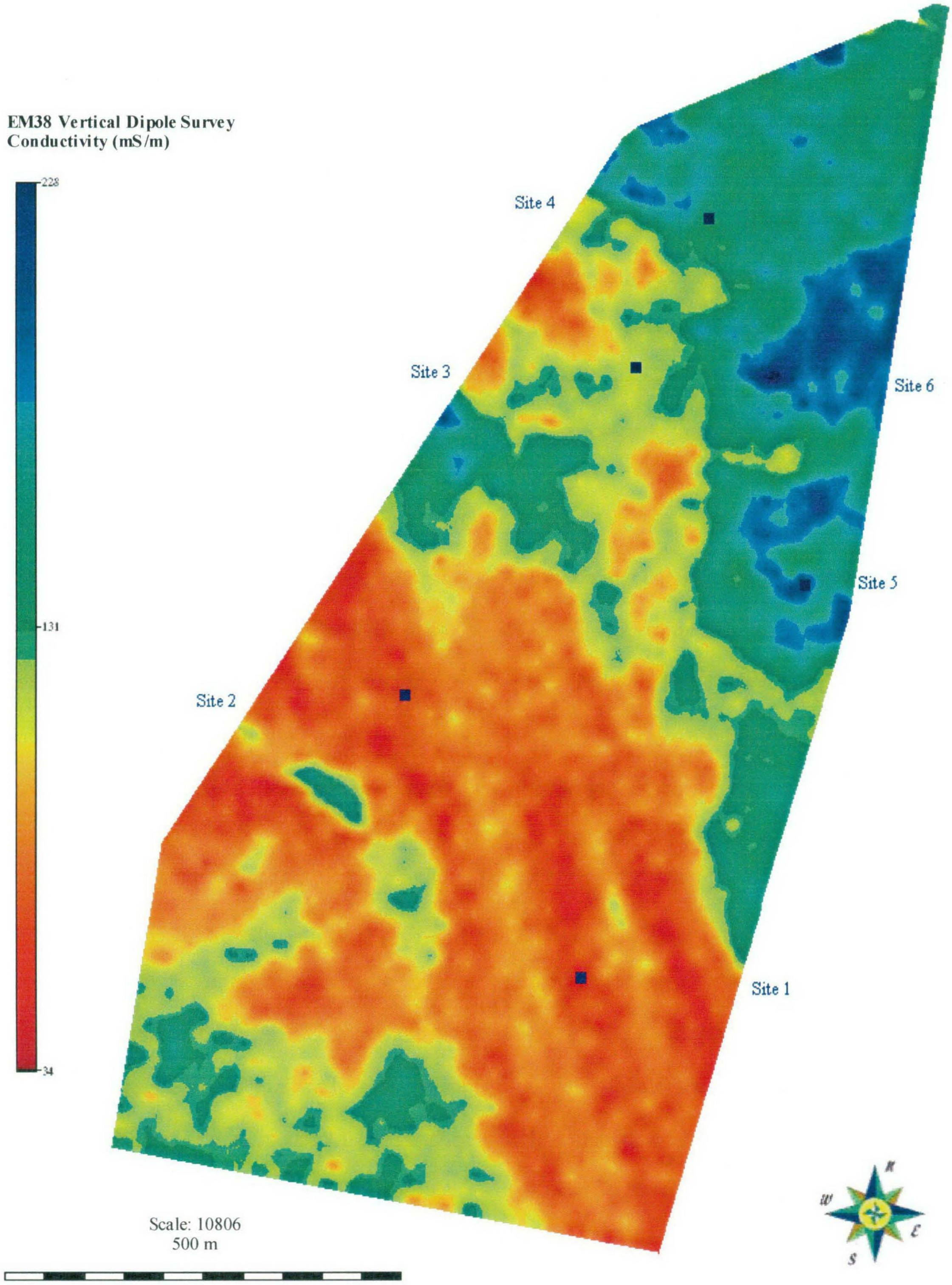


Figure 2-2 Digital multi-spectral imagery survey of the experimental field, located at Moreton Plains, Moree. Sampling sites are indicated by black squares.

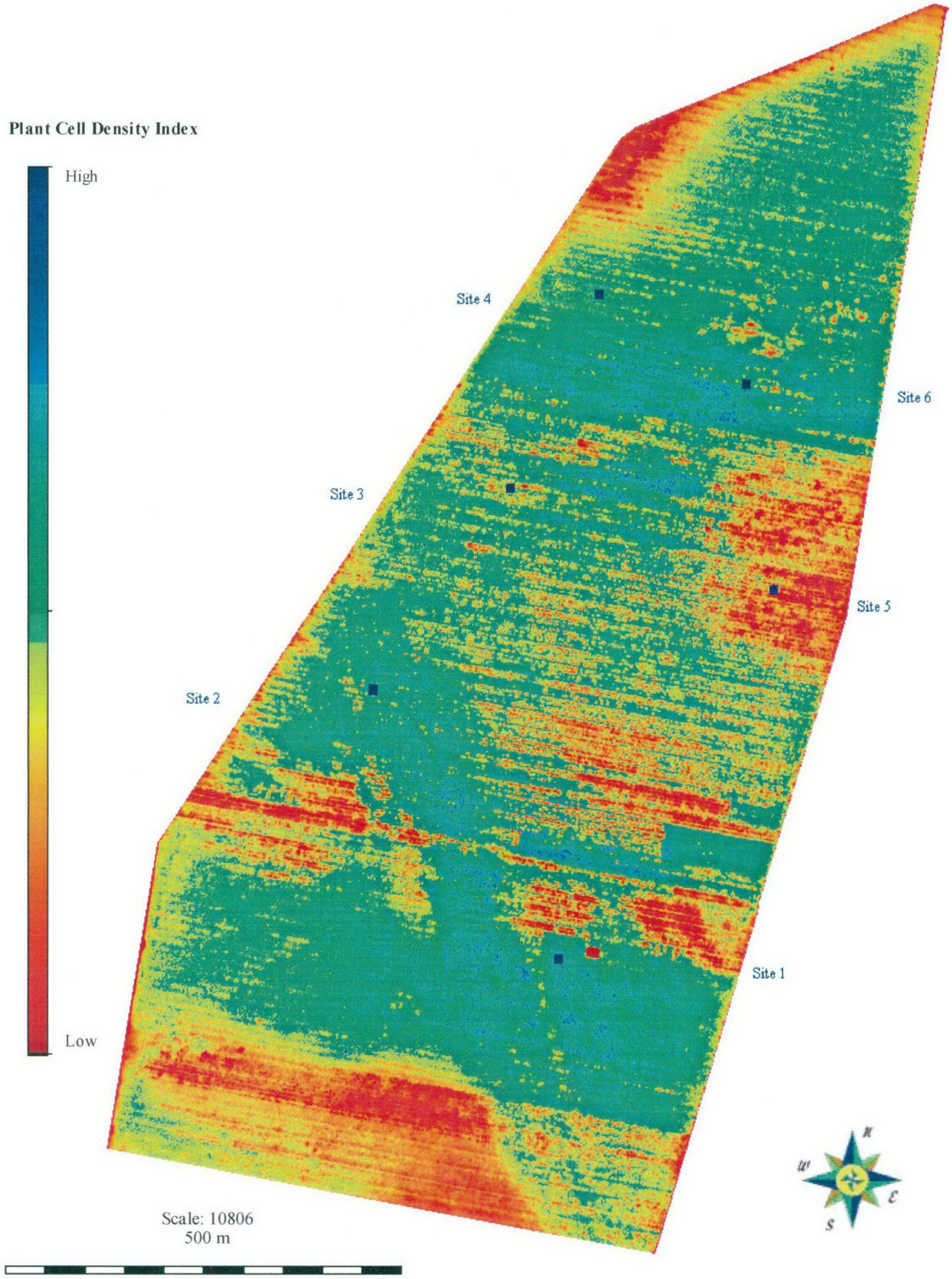


Table 2-1 Selected soil properties of samples taken from the experimental field, located at Moreton Plains, Moree. Sample sites were chosen on the basis of EM38 and DMSI surveys. Four soil samples were bulked together at each site and separated in 0-30 cm and 30-60 cm depth increments.

Site (No.)	Depth (cm)	Clay[a] (%)	pH[b] (H_2O)	pH[c] ($CaCl_2$)	P[d] (mg/kg)	ECse[e] (dS/m)	Ca[f] ($cmol_c$/kg)	K[f] ($cmol_c$/kg)	Na[f] ($cmol_c$/kg)	ECEC ($cmol_c$/kg)	ESP (%)	ESI[g]
1	0-30	30.9	7.6	7	31	1.2	22.3	0.6	0.2	29.5	0.7	0.32
	30-60	27.8	7.9	7.3	25	1.5	18.7	0.5	0.6	26.4	2.1	0.12
	Average	29.4	7.8	7.2	28	1.4	20.5	0.6	0.4	28.0	1.4	0.17
2	0-30	27	7.7	7.1	27	1	21.5	0.6	0.7	29.9	2.3	0.07
	30-60	23.5	8.2	7.4	31	0.6	17.5	0.5	0.7	25.5	2.7	0.04
	Average	25.3	8.0	7.3	29	0.8	19.5	0.6	0.7	27.7	2.5	0.06
3	0-30	31.5	8.4	7.7	26	1.5	24	0.7	1.6	35.4	4.4	0.06
	30-60	29.4	8.9	8.1	20	1.8	19.5	0.4	3.1	32.9	9.4	0.03
	Average	30.5	8.7	7.9	23	1.7	21.8	0.6	2.4	34.2	6.9	0.04
4	0-30	33	9	8.1	9.9	1.9	20	0.5	3.8	30.7	12.5	0.03
	30-60	48.2	9.3	8.4	5.0 *	2.0	14.5	0.4	9.6	31.5	30.3	0.01
	Average	40.6	9.2	8.3	7.5	2.0	17.3	0.5	6.7	31.1	21.4	0.02
5	0-30	35.6	9	8.1	17	2.2	20.5	0.6	4.8	32.7	14.6	0.03
	30-60	56.6	9.6	8.7	11	2.2	13	0.5	13	33.9	38.4	0.01
	Average	46.1	9.3	8.4	14	2.2	16.8	0.6	8.9	33.3	26.5	0.01
6	0-30	36.4	9.1	8.5	20	2.3	21.2	0.4	5.4	29.4	18.5	0.02
	30-60	42.7	9.5	8.9	12.6	2.4	14.7	0.5	14	32.9	42.7	0.01
	Average	39.6	9.3	8.7	16.3	2.4	18.0	0.5	9.7	31.2	30.6	0.01

[a] dispersion and sedimentation; [b] 1:5 soil: solution ratio in DI H_2O; [c] 1:5 soil: solution ratio in 0.01M $CaCl_2$; [d] Colwell (1966); [e] 1:5 soil: solution ratio in DI H_2O; [f] 1.0 M NH_4Cl (pH 8.5) Tucker (1972); [g] McKenzie (1998)

*** This site is likely to be P responsive; the critical soil concentration for cotton in Grey Vertosols is 6 mg/kg (Dorahy *et al.* 2002).**

2.2.2. *Plant measurements*

At each sample site, four plots, 1 m^2 in size were marked out around a central GPS coordinate. At squaring and harvest the youngest mature leaf (YML) was taken from each plant in the plot. When all of the fruit was mature, the plants were harvested, which involved removing the plants from the soil, rinsing them in deionised water and separating them into roots, tops and fruit. The roots were separated from the tops at the point on the stem where the cotyledon leaves were located. Due to the large rooting mass of cotton plants, it was impossible to remove all of the roots of each plant from the soil and as such only the main taproot of each plant was harvested, down to a depth of 30 cm below the soil surface.

2.2.3. *Determination of nutrient composition*

All sampled plant material was dried at 80°C, weighed and ground to <2 mm. The samples were digested with perchloric acid and hydrogen peroxide, using the sealed chamber method outlined by Anderson and Henderson (1986). The nutrient composition of the samples were analysed using the inductively coupled plasma atomic emission spectroscopy (ICPAES). An Australasian Soil and Plant Analysis Council (ASPAC) plant sample was included in the analysis, in order to ensure the accuracy of the digestion process.

2.2.4. *Statistical analysis*

In the analysis of this experiment, the means of the four replicates of each of the plant measurements were used in linear and exponential regression analyses, to determine the nature of the relationships between soil sodicity, crop growth and cotton nutrition ($P<0.05$). A multivariate analysis was carried out to determine the soil characteristics most significant in predicting soil sodicity in this field. T-tests, assuming equal variances, were used to determine the effect of harvest date on plant nutrient concentrations. Statistical analyses were carried out using the Genstat program (7th Edition, Lawes Agricultural Trust) (Payne 1987). Graphs were plotted using the Sigmaplot program (7th Edition, SPSS Inc.)

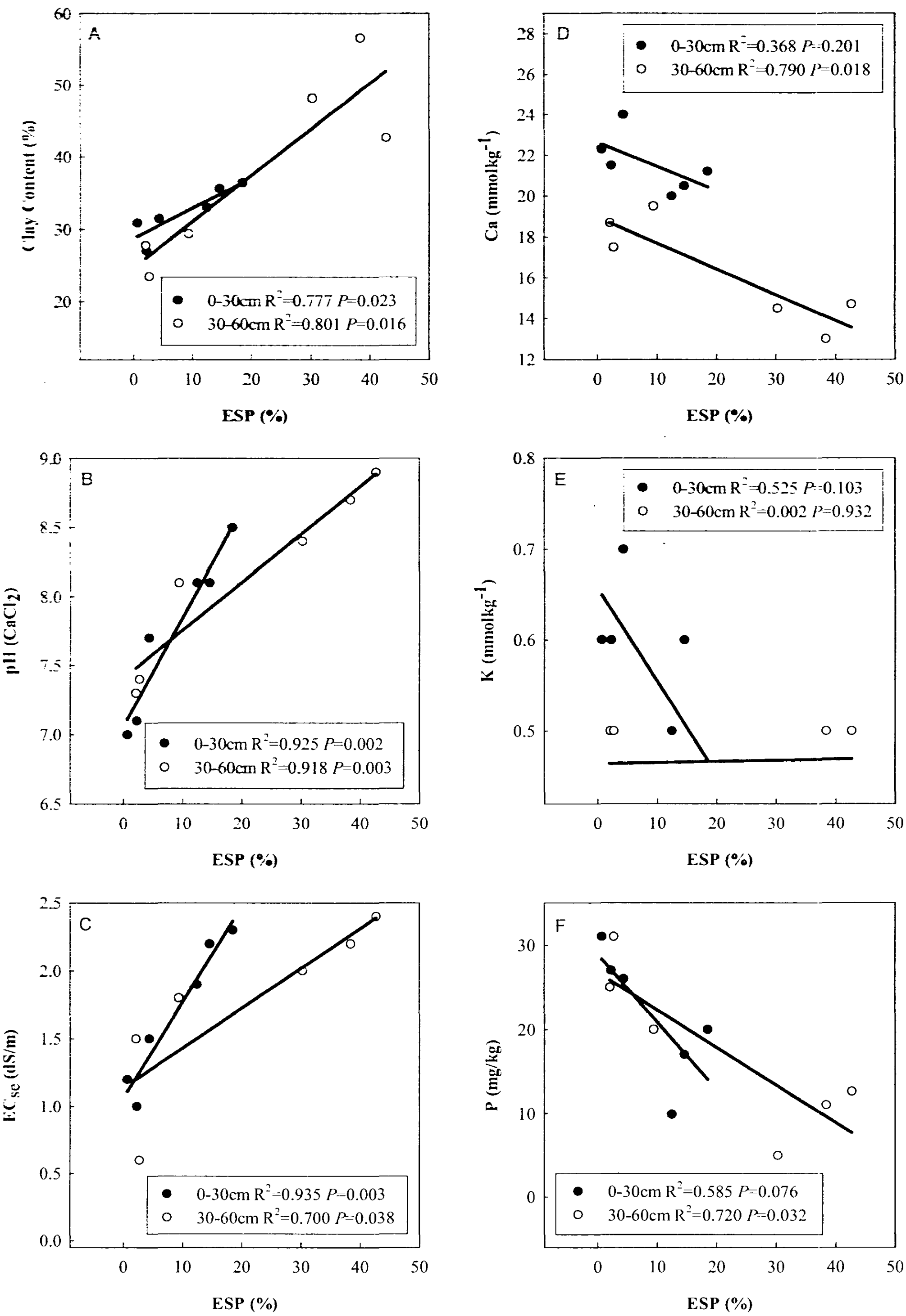
2.3. Results

2.3.1. *Soil properties*

The profile average sodicity levels of the selected field sites ranged from 1 to 31%, with the surface soil ESP ranging from 1 to 19% and the 30-60 cm depth ESP ranging from 2 to 43% (Table 2-1). Soil sodicity levels were positively linearly correlated with clay content, pH ($CaCl_2$) and EC_{se} at both the 0-30 and 30-60 cm soil depths ($P<0.05$) (Figure 2-3A to C). Surface soil Ca and P concentrations were not significantly related to sodicity but at a depth of 30-60 cm, soil Ca and P concentrations were negatively linearly correlated with soil sodicity ($P<0.05$) (Figure 2-3D and F). No significant correlations were apparent between soil sodicity and soil K concentration (Figure 2-3E).

Significant correlations were also apparent between other soil parameters; clay content was positively linearly correlated with EC_{se} at the surface ($P=0.002$; $R^2=0.928$) and in the 30-60 cm soil depth ($P=0.07$ and $R^2=0.60$), negatively exponentially correlated with P concentration in the 30-60 cm soil depth ($P=0.004$ $R^2=0.89$) and negatively linearly correlated with Ca concentration in the 30-60 cm soil depth ($P=0.01$ $R^2=0.84$). Additionally, EC_{se} was negatively linearly correlated with P concentration in the 30-60 cm soil depth ($P=0.03$ and $R^2=0.73$) and positively linearly correlated with pH in both the 0-30 cm ($P=0.003$ $R^2=0.92$ and 30-60 cm ($P=0.02$ $R^2=0.76$) soil depths. The soil factors most significant in predicting soil sodicity in this field, as determined by a multivariate regression analysis, were clay content ($P=0.01$) and pH ($P=0.01$), with these two factors predicting soil sodicity with a combined R^2 value of 0.92.

Figure 2-3 A to F: The relationships between the exchangeable sodium percentage of soils in the experimental field and their clay content, pH, electrical conductivity, calcium concentration, potassium concentration and phosphorus concentration. Data points correspond to a soil sample bulked from the four replicates at each site and separated into 0-30 cm and 30-60 cm depths.



2.3.2. *Plant growth*

There was a negative relationship between soil sodicity and the growth of this cotton crop, with the top (*P*=0.04) and fruit (*P*=0.03) dry matter accumulation of the crop at harvest decreasing with increasing soil sodicity (Figure 2-4A and B). The plants at the most sodic site produced 54% less dry matter and 62% less fruit than those in the least sodic site. Both the top dry matter accumulation and fruit production of the crop followed a similar pattern of decline with increasing soil sodicity, decreasing initially between the profile average ESP values of 1 and 7%, remaining relatively constant between ESP values of 7 and 27% and again decreasing in the most sodic field site.

The taproot dry weights of the plants in this field were not significantly related to soil sodicity (*P*=0.12) (Figure 2-4C). The average taproot dry weight measured at the two most sodic sites was however 56% greater than the average taproot dry weight measured in the sites with profile average ESP values between 1 and 21%. Visually, the taproots of the plants in the two most sodic treatments appeared greatly thickened and exhibited horizontal root growth below the soil surface (Figure 2-5).

2.3.3. *Nutrient concentrations and accumulation*

<u>Calcium</u>

The Ca concentrations of this cotton crop varied between the different sampling sites in all of the sampled plant parts. There was no direct relationship between cotton Ca concentrations and sodicity however, with the plant Ca concentrations varying independently of soil sodicity (*P*>0.05) (Figure 2-6). Cotton YML Ca concentrations increased between squaring and harvest, across the range of field sites (*P*<0.01). The Ca accumulated in the cotton tops decreased significantly with increasing soil sodicity (*P*=0.02), with the plants in the most sodic field site accumulating 43% less top Ca than the plants in the least sodic field site.

Figure 2-4 A to C The relationships between soil exchangeable sodium percentage and the top, fruit and taproot dry weights at harvest of commercially produced cotton (*Gossypium hirsutum* L.) grown within the one field. Values are means of four replicates.

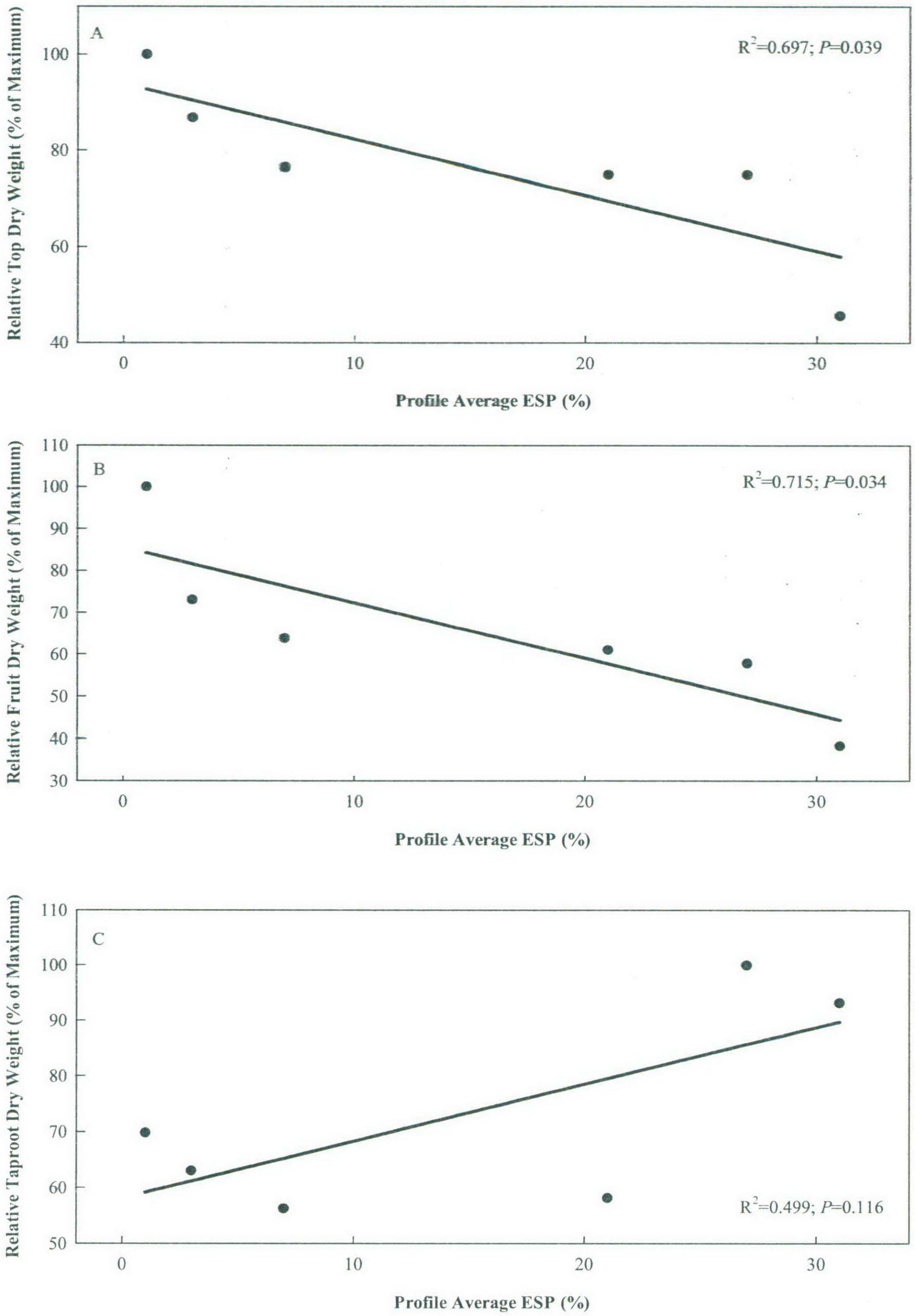
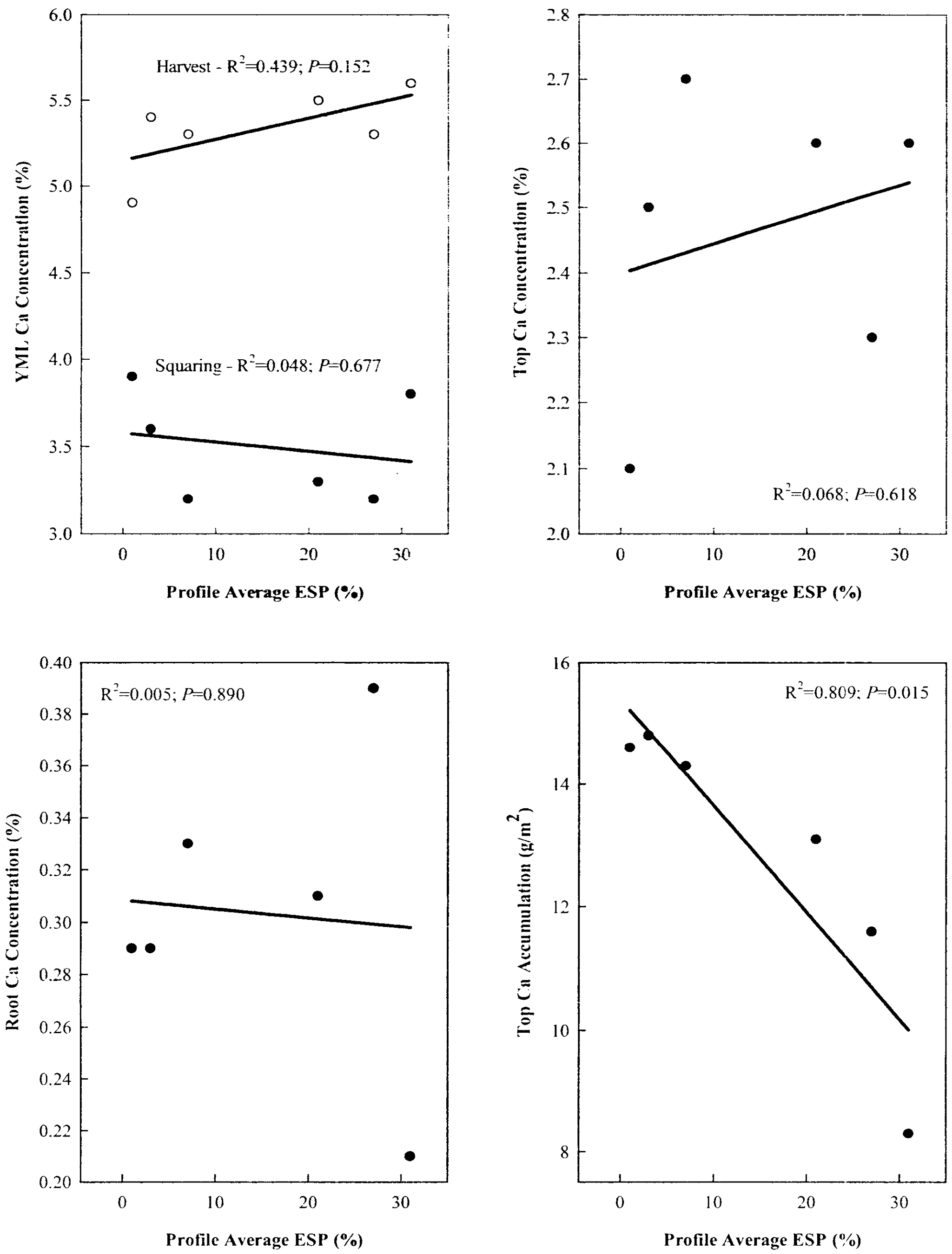


Figure 2-5 A photograph of the thickened roots and horizontal root growth observed in the cotton (*Gossypium hirsutum* L.) plants harvested from field sites with profile average ESP values of 27 and 31%.

Figure 2-6 The relationships between soil exchangeable sodium percentage and the youngest mature leaf, top and taproot calcium concentrations and top calcium accumulation of commercially produced cotton (*Gossypium hirsutum* L.). Values are means of four replicates.



Sodium

Soil sodicity was associated with increasing crop Na concentrations in all plant parts and across the range of field sites ($P<0.002$) (Figure 2-7). Cotton YML Na concentrations remained stable as the plants matured at low to moderate sodicity levels ($P>0.05$). At profile average ESP values of 21% and above however, the cotton YML Na concentrations increased between squaring and harvest ($P<0.05$). Soil sodicity was also associated with increased accumulation on Na in cotton tops ($P=0.002$) but this effect was most significant at profile average ESP values less than 27% (Figure 2-7).

Potassium

The response of cotton K concentrations to soil sodicity differed between the various plant parts sampled (Figure 2-8). There was a negative linear relationship between soil sodicity and early season ($P=0.01$) and harvest ($P=0.004$) YML K concentrations. The greatest decreases in YML K concentrations occurred at profile average ESP values up to 21%, with YML K concentrations tending to remain relatively stable in the two most highly sodic field sites. At low sodicity levels, YML K concentrations remained stable or slightly increased as the plant matured, but at profile average ESP values of 7% and above YML K concentrations were reduced between squaring and harvest ($P<0.05$). There was no significant relationship between soil sodicity and top ($P=0.26$) or root ($P=0.21$) K concentrations, although there was a trend towards decreasing top and root K concentrations at low to moderate ESP values and increasing top and root K concentrations at high ESP values (Figure 2-8). Increasing soil sodicity was however associated with an exponential decrease in cotton top K accumulation ($P=0.02$).

Figure 2-7 The relationships between soil exchangeable sodium percentage and the youngest mature leaf, top and taproot sodium concentrations and top sodium accumulation of commercially produced cotton (*Gossypium hirsutum* L.). Values are means of four replicates.

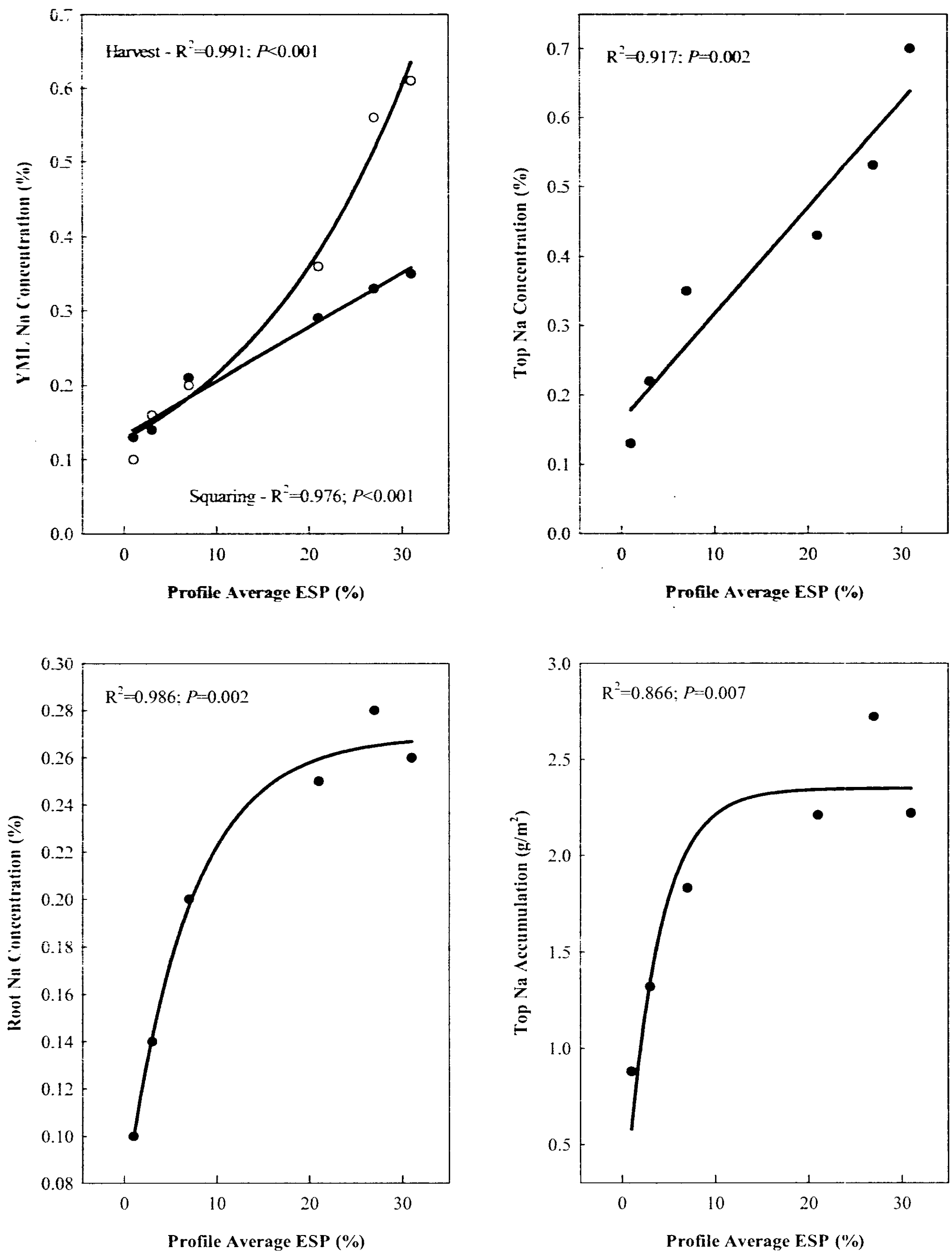
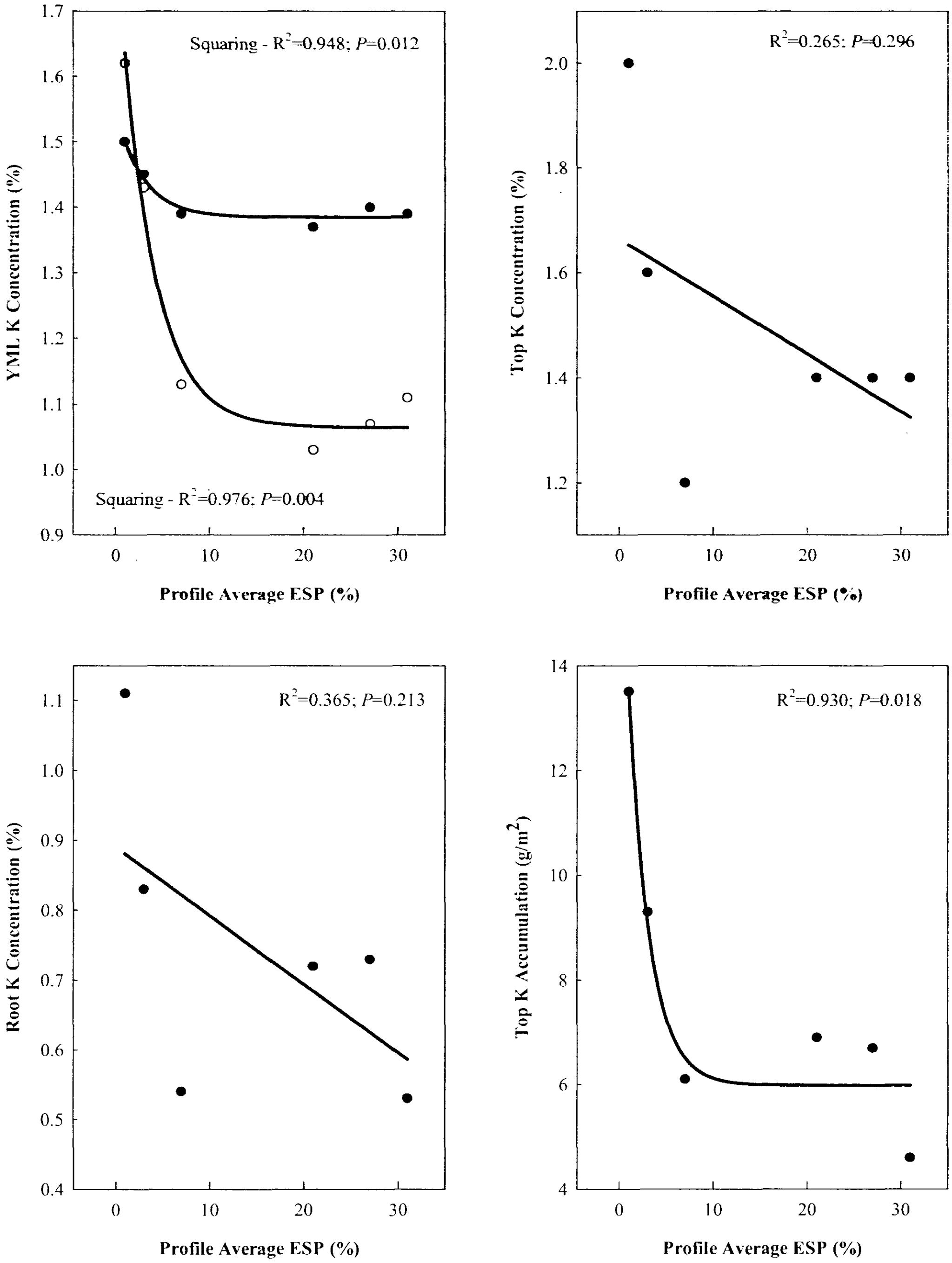


Figure 2-8 The relationships between soil exchangeable potassium percentage and the youngest mature leaf, top and taproot potassium concentrations and top sodium accumulation of commercially produced cotton (*Gossypium hirsutum* L.). Values are means of four replicates.



Phosphorus

The response of cotton P concentrations to soil sodicity differed between the various plant parts sampled (Figure 2-9). There was a significant negative linear relationship between harvest YML P concentrations and soil sodicity (P=0.003) but squaring YML (P=0.55), top (P=0.83) and root (P=0.29) P concentrations were not significantly related to soil sodicity. Top and root P concentrations did however tend to decrease with increasing soil sodicity at low to moderate ESP values and increase with sodicity at high ESP values (Figure 2-9). At low to moderate sodicity levels YML P concentrations increased between squaring and harvest (P<0.05) but at profile average ESP values of 21% and above YML P concentrations decreased between squaring and harvest (P<0.05). Increasing soil sodicity was associated with an exponential decrease in cotton top P accumulation (P=0.02).

Micronutrients

There was a positive linear relationship between soil sodicity and the B concentrations of the harvest cotton YMLs (P=0.01) and tops (P<0.001) across the range of sodicity levels in this field (Figure 2-10). There was however no significant relationship in this field between soil sodicity and cotton root B concentrations (P=0.36) or YML B concentrations at squaring (P=0.11). The amount of B accumulated by the cotton tops was generally negatively related to soil sodicity, with the cotton in the most sodic site accumulating 33% less B than the plants in the other field sites but the relationship between soil sodicity and top B accumulation was not significant (P=0.18). The B concentrations of the cotton YMLs increased significantly between squaring and harvest, across the range of soil sodicity levels (P<0.05).

Figure 2-9 The relationships between soil exchangeable sodium percentage and the youngest mature leaf, top and taproot phosphorus concentrations and top phosphorus accumulation of commercially produced cotton (*Gossypium hirsutum* L.). Values are means of four replicates.

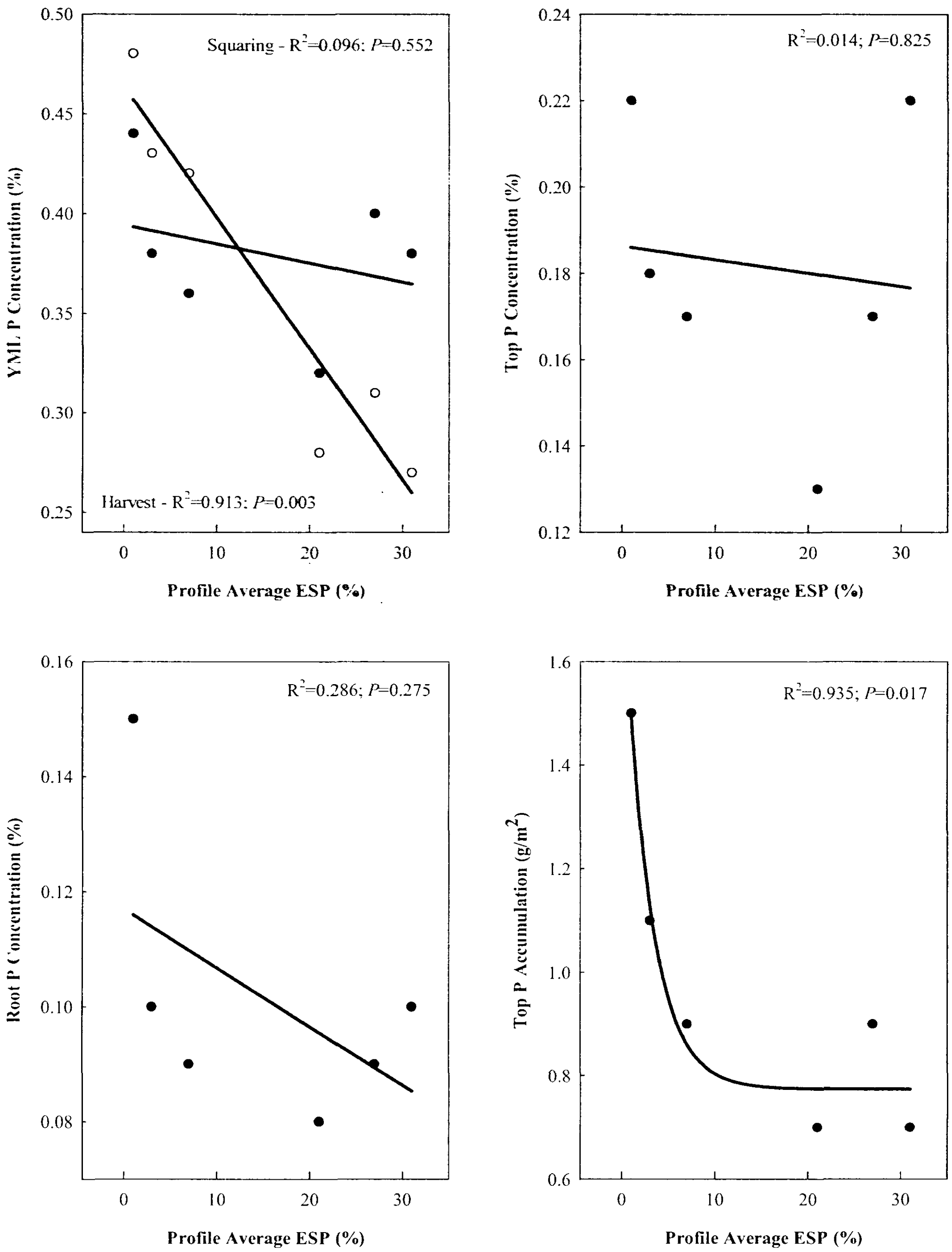
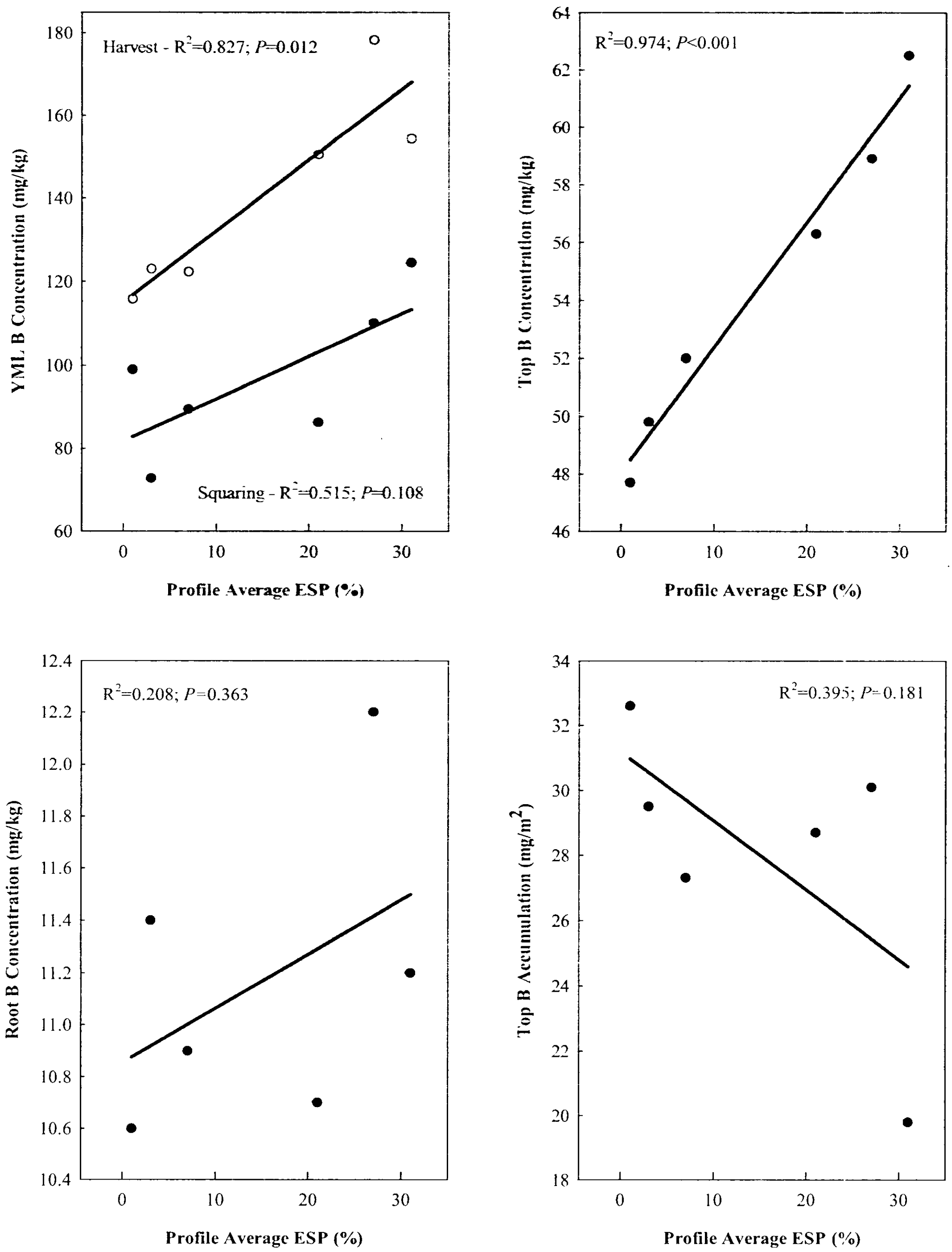


Figure 2-10 The relationships between soil exchangeable sodium percentage and the youngest mature leaf, top and taproot boron concentrations and top boron accumulation of commercially produced cotton (*Gossypium hirsutum* L.). Values are means of four replicates.



In this field, harvest YML Zn concentrations were negatively related to soil sodicity (P=0.003) but there was no significant relationship between soil sodicity and the top (P=0.94), root (P=0.31) or squaring YML (P=0.70) Zn concentrations (Figure 2-11). There was no significant relationship between soil sodicity and the top accumulation of Zn in cotton plants in this field (P=0.29) but the plants in the most sodic site accumulated an average of 62% less Zn than those in the other parts of the field. The cotton YML Zn concentrations increased significantly between squaring and harvest in the field sites with low to moderate levels of soil sodicity (P<0.05) but at profile average ESP values of 21% above, there was no significant effect of harvest date on YML Zn concentrations (P>0.05).

There were significant variations in the Fe and Mn concentrations of the plants at the different field sites, but there was no significant relationship between sodicity and the concentrations of these nutrients in the crop (P>0.05) (Figure 7-12 and 7-13). There were also significant variations in the top Fe and Mn accumulation of the plants in this field, but again there was no significant relationship between Fe and Mn top accumulation and sodicity. Between squaring and harvest the YML Fe concentrations decreased at low to moderate sodicity levels (P<0.05) but there was no significant effect of crop maturity on the YML Fe concentrations in the two most sodic sites (P>0.05). The cotton YML Mn concentrations increased with crop maturity in all but the most sodic site, where crop YML Mn concentrations decreased as the crop matured (P<0.05).

Figure 2-11 The relationships between soil exchangeable sodium percentage and the youngest mature leaf, top and taproot zinc concentrations and top zinc accumulation of commercially produced cotton (*Gossypium hirsutum* L.). Values are means of four replicates.

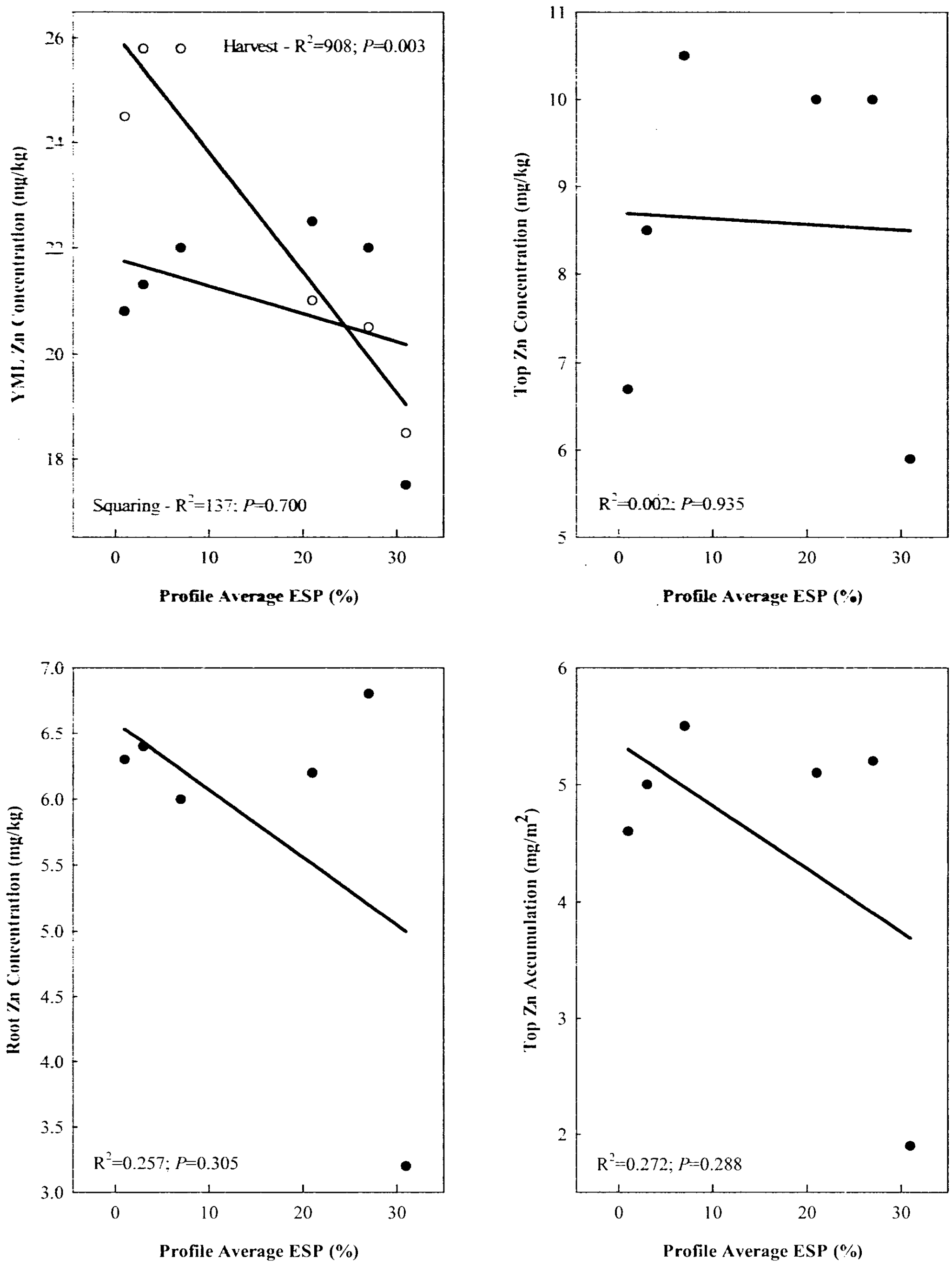


Figure 2-12 The relationships between soil exchangeable sodium percentage and the youngest mature leaf, top and taproot iron concentrations and top iron accumulation of commercially produced cotton (*Gossypium hirsutum* L.). Values are means of four replicates.

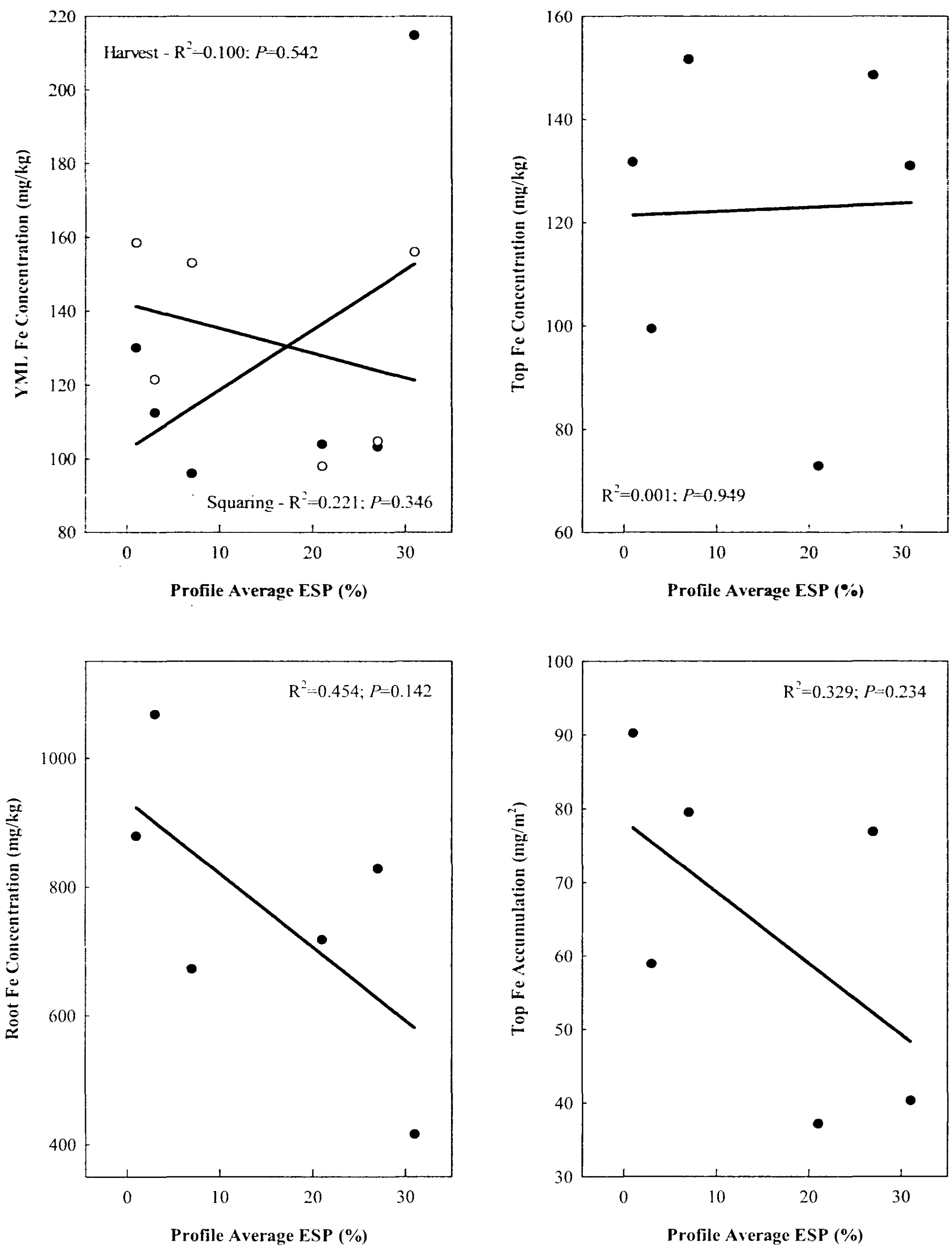
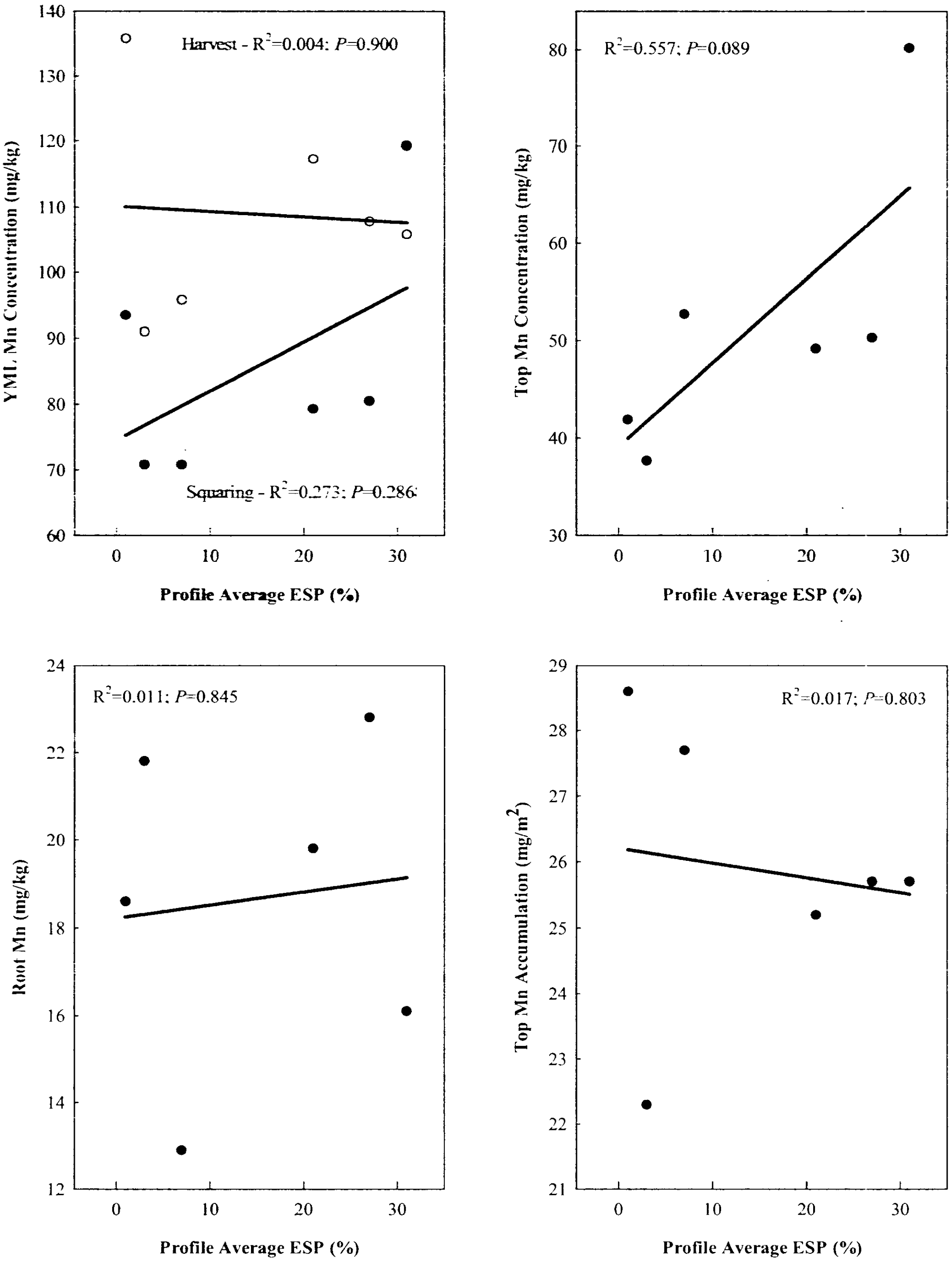


Figure 2-13 The relationships between soil exchangeable sodium percentage and the youngest mature leaf, top and taproot manganese concentrations and top manganese accumulation of commercially produced cotton (*Gossypium hirsutum* L.). Values are means of four replicates.



2.4. Discussion

2.4.1. *Soil properties*

A significant increase in soil pH (1:5 $CaCl_2$), from 7.0 to 8.9, occurred in this field with increasing soil sodicity. This relationship is important because it has ramifications for micronutrient availability. Increases in soil pH with increasing soil sodicity occur in soils containing carbonates, largely due to the displacement of adsorbed Ca and precipitation of carbonates with increasing soil Na concentrations (Guerrero-Alves *et al.* 2002). A similar pH response to increasing soil sodicity was observed in the artificially sodified soil created using the method outlined in Chapter 3. For example, the pH of the artificially sodified soil rose from 7.3 to 7.9, when analysed in solutions where soil solution Na and Ca concentrations were matched, as the soil ESP increased from 3 to 24% (Table 3-4), while in the field soil analysed in the current experiment a pH increase from 7.3 to 8.4 in $CaCl_2$ was observed with an increase in ESP from 3 to 27% (Table 7-1). The correspondence between the pH values observed in artificially sodified and naturally sodic soils suggests that artificial sodification processes used in experimental situations should be accompanied by increasing soil pH values, in order to closely mirror field conditions. The pH increases of artificial sodification methods should not however be amplified through the addition of bicarbonate to the soil, as this may create extreme increases in soil pH with sodicity. For example, Wright and Raiper (2000) used $NaHCO_3$ salt to sodify a clay loam; they raised the soil ESP from 1 to 38% but also increased pH (1:5 soil: water) from 6.3 to 8.7.

The P status of soils has commonly been found to decrease with increasing soil sodicity (Naidu *et al.* 1996; Rochester Unpublished), despite the increased availability of P in sodic soils observed by Curtin *et al.* (1992a) and Gupta *et al.* (1990), due to the dissolution of Ca-P compounds and the release of sorbed P. The nature of the relationship between sodicity and decreasing soil P status in field soils remains undetermined, but it is likely that the frequent occurrence of waterlogging in sodic soils contributes to this relationship. Phosphorus availability in Vertosols is driven by sorption processes with the Fe and Al oxide surfaces of the soil (Dorahy *et al.* 2002). The decrease in bicarbonate extractable P measured in this soil with increasing sodicity is most likely associated with occlusion of P as a result of waterlogging and oxide dissolution and reprecipitation during prolonged wetting and drying cycles. This issue has been highlighted in flooded rice production (Willett 1982). It is also possible however that the reductions in crop growth occurring in sodic soils as a result of their poor physical and chemical fertility (Figure 2-9), results in lower P return in litter and a smaller amount of labile P in the soil. The decreasing P status of the soil in this field with increasing soil sodicity has ramifications for the P nutritional status of the crop. The critical soil P concentration for cotton production in Grey Vertosols is 6 mg/kg (Dorahy *et al.* 2002), which suggests that site 4, with an ESP of 21% may be P responsive. The plants in site 4 had the lowest P concentrations of in the field, with an average mid-season YML P concentration of 0.32% and a harvest P concentration of 0.28%. Phosphorus is considered to be limiting to cotton growth at mid-season YML concentrations of less than 0.28% (Reuter and Robinson 1986), indicating that the plants in site 4 were bordering on P deficiency, in agreement with the predictions made from the soil data .

Increasing soil sodicity is also commonly associated with increasing soil salinity (Naidu *et al.* 1996; Rochester Unpublished) and this relationship frequently confounds sodic field experiments, as salinity itself significantly influences the physical and chemical characteristics of the soil. A significant correlation between sodicity and the soil EC was measured in this field in both the 0-30 and 30-60 cm soil depths, but the range of EC_{se} values present was only 0.6 to 2.4 dS/m. These salinity levels are well within the range at which soils are considered non-saline and the growth of moderately salt-tolerant plants, such as cotton, is not affected (Richards 1954). Increasing soil EC also has the potential to improve the physical condition of sodic soils (Loveday 1976). An electrochemical stability index (ESI) of <0.05 indicates that a soil is likely to be dispersive (McKenzie 1998). In this particular field, increases in soil EC may have marginally improved the physical condition of the soils with low ESP values, but all of the soils with ESP values greater than 5 had ESI values of less than 0.05, regardless of increasing soil EC and are thus likely to be dispersive (Table 2-1).

No significant correlations existed in this field between sodicity and the soil concentrations of K. This is important, as any observed differences in the K nutrition of the plants sampled at the different sites are thus not attributable to changing soil K status. Variation in soil K concentrations did however exist in this field.

The correlations between sodicity and other soil characteristics create difficulties in the interpretation of field experiments. This experiment is however useful in illustrating the types of relationships that exist in cotton fields, between crop growth and nutrition and soil sodicity. Additionally, the results of the current experiment informed the design of the experiments outlined in Chapters 4, 5, 6 and 7, which have subsequently determined the effects of the physical and chemical characteristics of sodic soils on cotton growth and nutrition and the mechanisms responsible for these effects, in more controlled environments. The results of Chapters 4 – 7 are used in Chapter 8 to draw sound conclusions regarding causal relationships between the soil data and cotton plant responses measured in the current experiment.

2.4.2. *Plant growth*

This experiment characterised the relationships between the growth and nutrition of a cotton crop and increasing soil sodicity, in a field situation. The location of all of the sample sites within the one field minimised the variations imposed on the experiment due to differences in climate and crop management. In this field, increasing sodicity was related to a 24% reduction in top dry weight and a 36% reduction in fruit dry weight at ESP levels between 1 and 7% but further increases in sodicity up to an ESP of 27% tended not to further limit cotton growth (Figure 2-4). At ESP values between 27 and 31% there was a further 29% reduction in cotton top dry weight and a further 20% reduction in cotton fruit dry weight. In broad program of field sampling, Rochester (Unpublished) measured an average decrease in cotton dry matter accumulation of 23% and an average decrease in cotton fruit production of 22% with an ESP increase of 2 to 22%. The reductions in cotton dry matter accumulation and fruit production measured at ESP values of up to 27% in the current experiment are similar to those observed by Rochester (Unpublished). The effects of sodicity on the yield of a cotton crop depends upon the individual soil profile characteristics, climatic conditions and management practises occurring in a particular site, but similarities between the results obtained in this experiment and that carried out by Rochester (Unpublished) suggest that the figures obtained in these experiments can be used as a guide to estimate the possible effects of soil sodicity on cotton crop performance at different locations.

Poor soil physical condition in sodic soils with ESP levels of up to 22%, has also been implicated in cotton and soybean yield reductions in Vertosols in the Hillston (Muller 2005) and Condobolin (McKenzie *et al.* 2002a) districts of southern NSW. Muller (2005) observed a 15% reduction in cotton yield with an increase in soil ESP from 3.3% to 5.4% in the top 40 cm and from 18.9% to 22.1% in the 40-80 cm profile depth. This yield reduction was correlated with an increase in surface soil dispersible clay from 12.1% to 17.1%. Similarly, McKenzie *et al.* (2002a) measured a 50% yield reduction in soybean plants produced under border check irrigation at ESP values between 8.6% and 10.7%, due to surface crusting and waterlogging. The NLWRA (2002) describes a relative yield function for sodicity, which relates surface ESP to the average relative yield of 30 crop and pasture species. This function predicts a yield reduction of between 20% and 45% due to soil sodicity at an ESP of 20%, which is broadly similar to the results obtained in this experiment and those outlined by Rochester (Unpublished). It is interesting to note that in the current experiment reductions in cotton yield were related to increases in soil sodicity at ESP levels less than that which would be classified as sodic (ESP < 6%).

There was no significant relationship between sodicity and taproot dry weight in the current experiment. Visually however, the taproots of the plants in the two most sodic field sites appeared greatly thickened when compared to those of the plants in the sites of lower soil sodicity. In contrast to the sites with ESP values of up to 7%, the two most sodic sites had sodic surface soils and surface ESI values indicating that they were dispersive (ESI<0.05) (McKenzie 1998). It appears that the high soil strength occurring in these highly sodic soils, due to the dispersion of clay particles, resulted in larger and thicker taproots (Figure 2-5), as high soil strength causes root cells to enlarge radially rather than axially (Clark *et al.* 2003).

A combination of both the adverse physical and chemical characteristics of sodic soils has been shown to induce nutrient deficiencies and toxicities in plants (Curtin and Naidu 1998). Sodicity causes structural deterioration of the soil, reducing hydraulic conductivity and increasing susceptibility to surface crusting, hard setting and waterlogging (Levy *et al.* 1998). These factors can limit plant productivity by reducing seedling emergence and root activity. Sodic soils also can have low redox potential, high soil pH and high soil solution Na concentrations (Curtin and Naidu 1998). These factors can also limit plant productivity by changing the availability of nutrients to plant roots. Field experiments, such as the current experiment and those outlined by Rochester (Unpublished) and Muller (2005) are useful in quantifying the likely effects of sodic soils on the productivity of cotton crops in field situations. These experiments do not however determine the mechanisms responsible for reductions in cotton performance in sodic soils. In order to better understand the mechanisms behind declining crop performance in sodic soils, there is a need quantify the relative contribution of the adverse physical and chemical characteristics of sodic soils to the growth of crop plants. The glasshouse experiments outlined in Chapters 4, 5, 6 and 7 were carried out to address these questions. The implications of the results of these glasshouse experiments for cotton growth in field production situations, such as the field described in the current experiment, are discussed in Chapter 8.

2.4.3. *Nutrient concentrations and accumulation*

Calcium

There was no significant relationship between sodicity and the Ca concentrations of cotton in this field, despite variation in the plant Ca concentrations at the different field sites. The YML Ca concentration at which cotton is considered to be suffering from Ca deficiency is approximately 1.9% (Reuter and Robinson 1986). All of the plants in this experiment exhibited YML Ca concentrations well above this level throughout the season and as such Ca deficiency did not limit cotton growth in this field, despite the significant decreases in soil Ca concentrations that occurred in this field with increasing soil sodicity. A reduction in the top Ca accumulation of cotton was related to increasing soil sodicity in this field, but given the Ca concentrations results, it is likely that this occurred as a result of reductions in dry matter accumulation, rather than any limitations to Ca availability.

The results of this experiment differ from that obtained by Rochester (Unpublished), in that this author observed decreasing cotton YML Ca concentrations with increasing soil sodicity. Similarly to the current experiment however Rochester (Unpublished) found no Ca deficiency at any sodicity level in his experiment. Thus, given the range of sites sampled in these two experiments, it can be concluded that it is unlikely that Ca deficiency will limit cotton performance in the sodic soils commonly utilised for cotton production in NSW, despite the variable response of cotton Ca concentrations to sodicity in different field situations. This outcome is supported by the experiments outlined by Kopittke and Menzies (2005a) and Kopittke *et al.* (2005b) which relate the performance of mungbeans (*Vigna radiata* L.) and rhodes grass (*Chloris gayana* L.) to the calcium activity ratio (CAR) of soil solutions. This work highlights the broad range of soil solution Ca activities and ratios over which plant growth response remains unaffected.

Although it appears unlikely from the results of the current experiment that Ca nutrition limits cotton crop productivity in sodic Grey Vertosols, further experimentation, addressing the questions of the individual effects of sodic soil solution chemistry and sodic soil physical condition on the Ca nutrition of cotton are outline in Chapters 4, 5, 6 and 7. The implications of the results of these glasshouse experiments for the interpretation of the Ca nutrition results of the current experiment are discussed in Chapter 8.

Sodium

The majority of the agriculturally significant varieties of cotton are Na-including plants, which means that one of their central mechanisms of tolerance to sodic conditions is to accumulate significant quantities of Na and sequester this nutrient within plant structures (Lauchli and Stelter 1982; Leidi and Saiz 1997). Similarly, the concentrations of Na present in all of the plant tissues sampled in this experiment, increased significantly with increasing soil sodicity across the range of field sites (Figure 2-7).

The increases in YML Na concentrations that occurred as the cotton plants matured in the most sodic sites, can probably be explained by the large increases in ESP with depth that occurred in these areas. Increases in sodicity with profile depth also occurred in the less sodic areas, but these increases were amplified in magnitude as the profile average ESP increased. For example, in the least sodic site the ESP of the soil rose from 0.7 to 2.1% from 0-30 cm to 30-60 cm depth but in the most sodic site the ESP of the soil rose from 18.5 to 42.7% with depth (Table 2-1). As the plant root systems expanded and accessed more sodic soil further down the profiles with ESP values of 21% and greater, plant Na concentrations rose accordingly.

The cotton Na concentrations, at which sodicity becomes chemically limiting to cotton production, have not been established with certainty, due to the difficulty in separating high levels of soil Na from other factors, including poor soil physical condition and salinity. In this experiment, reductions in cotton dry weight accumulation and fruit production, occurred at mid-season YML Na concentrations greater than 0.13%, but soil physical factors may have significantly contributed to decreasing cotton growth at these low ESP values. The large decreases in cotton growth that occurred at the most sodic site corresponded to early season YML Na concentrations of approximately 0.3%. Mid-season YML Na concentrations were negatively correlated with dry matter accumulation (P=0.04) and fruit production (P=0.03) in this field (Figure 2-14A). Similarly, top Na concentrations were negatively correlated with dry matter accumulation (P=0.004) and fruit production (P=0.01) in this cotton crop (Figure 2-15A). The correlations between the top Na concentrations of the crop and cotton performance were stronger than for any other nutrient (R^2 values of 0.90 and 0.88 respectively) but no clear causal relationships between cotton Na concentrations and cotton growth were demonstrated, due to the presence of complicating factors, such as poor soil physical condition. As such, a number of factors, perhaps including the accumulation of toxic concentrations of Na, are responsible for the decreasing cotton performance observed in these sodic soils.

Further experimentation, addressing the question of the effects of increasing plant concentrations of Na on cotton productivity and attempting to determine the threshold YML Na concentrations at which cotton productivity is reduced are outline in Chapters 4, 5, 6 and 7. The implications of the results of these glasshouse experiments for the interpretation of the Na nutrition results or the current experiment are discussed in Chapter 8.

Potassium

Sodicity affected the K nutrition of cotton in this field. A significant relationship was apparent between sodicity and exponentially decreasing cotton YML mid-season and harvest K concentrations (Figure 2-8). In the highly sodic soils of this field however, further increases in sodicity had no additional effect on YML K concentrations. The mid-season YML K concentration at which cotton is considered to be suffering from a K deficiency is 1.5% (Reuter and Robinson 1986). The YML K concentrations of this crop fell below this level in all of the sites in this field but the least sodic. This result indicates that K nutrition was limiting to cotton performance at the sites with profile average ESP values ranging from 3 to 31%.

Despite the YML K results, there were no significant linear or exponential relationships between soil sodicity and the top or root K concentrations of cotton in this field. At low to moderate sodicity levels, cotton top and root K concentrations tended to decrease with increasing soil sodicity but at high sodicity levels, cotton top and root K concentrations tended to increase with increasing soil sodicity (Figure 2-8). The total K accumulated by cotton tops in this field was however significantly negatively exponentially related to soil sodicity. The most likely explanation for this pattern of nutrient accumulation is that in the highly sodic sites, the growth of the crop was more greatly limited than its ability to accumulate K, resulting in slight increases in crop K concentrations. This proposal is supported by the fact that the top dry weights of the plants in the site with an ESP of 31% were lower than at any other site and these plants also accumulated the lowest total amount of K in their tops. Another possible contributing factor to the slight improvement in top and root K status in the highly sodic soils is that the low hydraulic conductivity of the surfaces of these soils resulted in a failure of irrigation water to infiltrate and thus a lower frequency and/or severity of waterlogging events contributed to a slightly improved crop K status.

The mid-season YML K concentrations of the cotton in this field were positively correlated with fruit production (P=0.03) but not top dry matter accumulation (P=0.10) (Figure 2-14B) and top K concentrations were positively correlated with fruit production (P=0.06) but not top dry matter accumulation (P=0.16) in this cotton crop (Figure 2-15B). The relationship between YML K and cotton fruit production was stronger than for P and Zn YML nutrient concentrations (R^2=0.73) and comparable to that of YML Na concentrations (R^2=0.75). Additionally, the cotton with mid-season YML K concentrations greater than the critical level of 1.5% accumulated more dry matter and fruit than those with YML K concentrations of less than 1.5% (Figure 2-5B). No clear causal relationship between cotton K concentrations and cotton growth was demonstrated in this experiment however, due to the large number of variables present in the production system and the variable response of cotton K concentrations to sodicity at different ESP values. As such, it is likely that a number of factors, including deficient concentrations of plant K, are responsible for the decreasing cotton performance observed in these sodic soils. The results of this experiment do however suggest that declining crop K status is more significant in limiting cotton production in soils of low to moderate sodicity than it is in highly sodic soils.

The dispersive nature of sodic soils results in soil physical conditions that have the potential to limit the K nutrition of cotton. Sodic soils are frequently characterised by high soil strength (So and Cook 1993) and an increased susceptibility to waterlogging events (Jayawardane and Chan 1994) as restricted infiltration of water results in waterlogging in the surface soil layers and restricted internal drainage results in waterlogging in sodic subsoils (McIntyre 1979; McIntyre *et al.* 1982).. Kuchenbuch *et al.* (1986) determined that the total amount of K taken up by a plant decreases in soils of high strength, due to reduced exploration of the soil volume by the roots. Similarly, Hocking *et al.* (1987) and McLeod (2001) determined that K uptake by cotton decreases both during and after a waterlogging event due to the root damage and the decreases in root growth that occur in the anaerobic environment of a waterlogged soil (Wiengweera and Greenway 2004). The effects of sodicity on plant K nutrition have however also been attributed to soil chemical properties. Sodic soil chemical characteristics with the potential to limit the K nutrition of cotton include soil exchange equilibrium shifts reducing the K concentrations in the soil solution and low plasma membrane integrity resulting in the leakage of K from root cells (Cramer *et al.* 1985). Further experimentation, addressing the question of the mechanisms behind the declining K nutrition of cotton crops produced in sodic soils is outline in Chapters 4, 5, 6 and 7. The implications of the results of these glasshouse experiments for the interpretation of the K nutrition results of the current experiment are discussed in Chapter 8.

Phosphorus

Sodicity affected the P nutrition of cotton in this field. There was a significant negative relationship between soil sodicity and the P concentrations of the YMLs of cotton at harvest in this field (Figure 2-9). Phosphorus is not considered to be limiting to cotton growth at mid-season YML concentrations of greater than 0.28% (Reuter and Robinson 1986). Thus, all plants in this experiment had sufficient P concentrations and as such P deficiency did not limit cotton growth in this field, despite the significant decreases in YML P concentrations that occurred in this field with increasing soil sodicity.

Despite the YML P results, there was no significant linear relationship between soil sodicity and the top or root P concentrations of cotton in this field. At low to moderate sodicity levels, cotton top and root P concentrations tended to decrease with increasing soil sodicity but at high sodicity levels, cotton top and root P concentrations tended to increase with increasing soil sodicity (Figure 2-8). The total P accumulated by cotton tops in this field was however significantly negatively exponentially related to soil sodicity. There are a number of factors that may contribute to the patterns of P nutrition that occurred in this field. It is important to note that the P concentration of the soil declined from 31 and 25 mg/kg in the 0-30 and 30-60 cm increments respectively of the soil profile in the least sodic site, to 9.9 and 5.0mg/kg in the 0-30 and 30-60 cm increments respectively of the soil profile in the 21% ESP site (Table 2-1). The critical soil P concentration for cotton production in Grey Vertosols is 6 mg/kg (Dorahy *et al.* 2002) and as such, the low soil P fertility in the 21% ESP site probably contributed to the low P status of the crop. It is also possible that in the highly sodic sites, the growth of the crop was more greatly limited than its ability to accumulate P, resulting in increases in crop P concentrations. This proposal is supported by the fact that the top dry weights of the plants in the site with an ESP of 31% were lower than at any other site and these plants also accumulated the lowest total amount of P in their tops. Another possible contributing factor to the improvements in crop P status in the highly sodic soils is that the low hydraulic conductivity of the surfaces of these soils resulted in a failure of irrigation water to infiltrate and thus a lower frequency and/or severity of waterlogging events contributed to a slightly improved crop P status.

In contrast to the current experiment, in the experiment carried out by Rochester (Unpublished) the YML P concentrations of cotton tended to fall below the critical level at an ESP of approximately 10%. This discrepancy is possibly due to the relatively high fertility of the soils in all but site 4 of the current experiment (Table 2-1). No relationship was apparent in the current experiment between cotton YML or top P concentrations and crop performance (P>0.05) and there was a lack of correspondence between accepted mid-season YML P deficiency level of 0.28% and crop performance (Figures 2-14C and 2-15C). Thus, it appears that the P nutritional status of this crop was not responsible for the reductions in crop performance that occurred with increasing soil sodicity.

The dispersive nature of sodic soils results in soil physical conditions that have the potential to limit the P nutrition of cotton. Namely, sodic soils are frequently characterised by high soil strength (So and Cook 1993) and a susceptibility to waterlogging events (Jayawardane and Chan 1994). Cornish, So *et al.* (1984) determined that the total amount of P taken up by a plant decreases in soils of high strength, due to reduced root growth. Similarly, Hocking *et al.* (1987) and McLeod (2001) determined that P uptake by cotton decreases both during and after a waterlogging event due to root damage and reductions in root growth. The effects of sodicity on plant P nutrition have however also been attributed to chemical soil properties. A sodic soil chemical characteristic with the potential to limit the P nutrition of cotton is reductions in soil P concentrations in sodic soils (Naidu *et al.* 1996; Rochester Unpublished) possibly due to the occlusion of P during prolonged wetting and drying cycles and low organic P returns to the soil. Further experimentation, addressing the question of the mechanisms behind the declining P nutrition of cotton crops produced in sodic soils is outline in Chapters 4, 5, 6 and 7. The implications of the results of these glasshouse experiments for the interpretation of the P nutrition results of the current experiment are discussed in Chapter 8.

Micronutrients

The cotton B concentration results obtained in this experiment can be largely explained through accepted sodic soil chemistry. Soil solution B concentrations are determined by adsorption and precipitation reactions and these are controlled by pH, exchangeable cations, ionic strength and soil water content (Curtin and Naidu 1998). Increasing pH enhances adsorption of B onto clay minerals due to changes in soil solution B speciation (Hingston 1964). The adsorption of B onto clay minerals is reduced by soil solution Na and increased by soil solution Ca, at pH values >8 however (Keren and Gast 1981), which may lead to B toxicities in some sodic systems (Cartwright *et al.* 1986). The significant positive relationships between soil sodicity and the concentrations of B measured in this cotton crop illustrate a reduction in the absorption of B occurring in these soils due to rising soil concentrations of Na. Although not significant, the accumulation of B in the tops of the cotton plants in this experiment tended to decrease with increasing soil sodicity. Given the B concentration results of this experiment, it is likely that this result can be explain by reductions in plant dry matter accumulation with increasing soil sodicity.

The mid-season YML concentration at which B is considered to be limiting to cotton growth is between 20 and 60 mg/kg (Reuter and Robinson 1986) or 53 mg/kg (Rashid and Rafique 2002) with cotton responses to B fertilization varying across this range of plant concentrations (Woodruff 2004). Shoot B concentrations greater than 1110 mg/kg have been associated with B toxicity in cotton crops (Ayars *et al.* 1994). The B concentrations of this crop remained within the optimum range across the field sites in this experiment, indicating that plant B concentrations were not limiting to cotton growth in this field, at any sodicity level.

Zinc deficiency has been commonly reported in crops produced in sodic soils (Williams and Raupach 1983), due largely to the high pH values that are associated with soil sodicity (Curtin and Naidu 1998). The low Zn status of the cotton produced in the most sodic sites in this field can likely be explained by the pH values in excess of 9.0 (1:5 H_2O) that occur in these areas. Cotton YML Zn concentrations less than 20 mg/kg are indicative of Zn deficiency (Reuter and Robinson 1986). The Zn status of this crop was limiting to cotton performance in the most sodic field site and thus may have contributed to the decreasing cotton growth that occurred at this ESP value. The mid-season YML or harvest top Zn concentrations of this crop were not significantly related to its top dry matter accumulation or fruit production ($P>0.05$) (Figures 2-14D and 2-15D). Thus, although Zn deficiency may have contributed to reduced cotton performance at ESP levels greater than 27% in this field, a number of other factors are also responsible, possibly including poor soil physical conditions and accumulation of excess plant concentrations of Na.

Manganese and iron deficiencies have commonly been reported in sodic soils, due largely to the conditions of high pH that are associated with sodicity (Williams and Raupach 1983). No significant relationship was apparent in this field however, between soil sodicity and cotton Mn or Fe concentrations. The YML Mn and Fe concentrations at which deficiency of these nutrients becomes limiting to cotton performance are between 30 and 50 mg/kg respectively (Reuter and Robinson 1986). Manganese toxicity is likely to limit cotton performance at a whole shoot Mn concentration of 750 mg/kg (Reuter and Robinson 1986). The concentrations of these nutrients in the YMLs of the cotton plants at all of the sample sites remained within these levels throughout the season and as such the availability of Mn and Fe to the crop was not limiting to cotton performance and did not contribute to the decreasing performance of cotton with increasing soil sodicity that occurred in this field.

2.5. Summary – using sodic field production systems to inform glasshouse experimental design

Although no direct causal relationships between soil chemical characteristics and cotton performance can be drawn from this experiment, a comparison of this experiment and that carried out by Rochester (Unpublished) is useful in illustrating the types of growth and nutritional effects that sodic soils can have on cotton crops. This experiment is also important because it highlights the gaps in the current understanding of how sodicity affects the growth and nutrient accumulation of cotton. The results of this experiment and the program of field sampling carried out by Rochester (Unpublished) have informed the design of the glasshouse experiments outlined in chapters 4, 5, 6 and 7. The implications of the results of these glasshouse experiments for cotton growth and nutrition in field production situations, such as the field used in the current experiment, are discussed in Chapter 8.

There were two distinct responses of the cotton produced in this field to sodicity, depending upon the ESP of the soil. At ESP levels of up to a profile average of 21%, increasing soil sodicity was related to a 24% decline in dry matter accumulation and 36% decline in fruit production. Reductions in K concentrations to deficient levels and increases in crop Na concentrations also occurred with increasing soil sodicity at these ESP values. At ESP levels between profile averages of 21 and 31%, increasing soil sodicity corresponded to further declines of 29% in dry matter accumulation and 20% in fruit production. Reductions in crop Zn concentrations to deficient levels and increases in crop Na concentrations also occurred with increasing sodicity at ESP values between 21 and 31%. The results of the experiments outlined in Chapters 4, 5, 6 and 7 can be used to determine the relative importance of sodic soil physical and chemical characteristics in the responses of cotton to sodicity in this field.

Figure 2-14 A to D The relationships between the youngest mature leaf sodium, potassium, phosphorus and zinc concentrations of commercially produced cotton (*Gossypium hirsutum* L.) at squaring and the dry matter accumulation and fruit production at harvest. Values are means of four replicates.

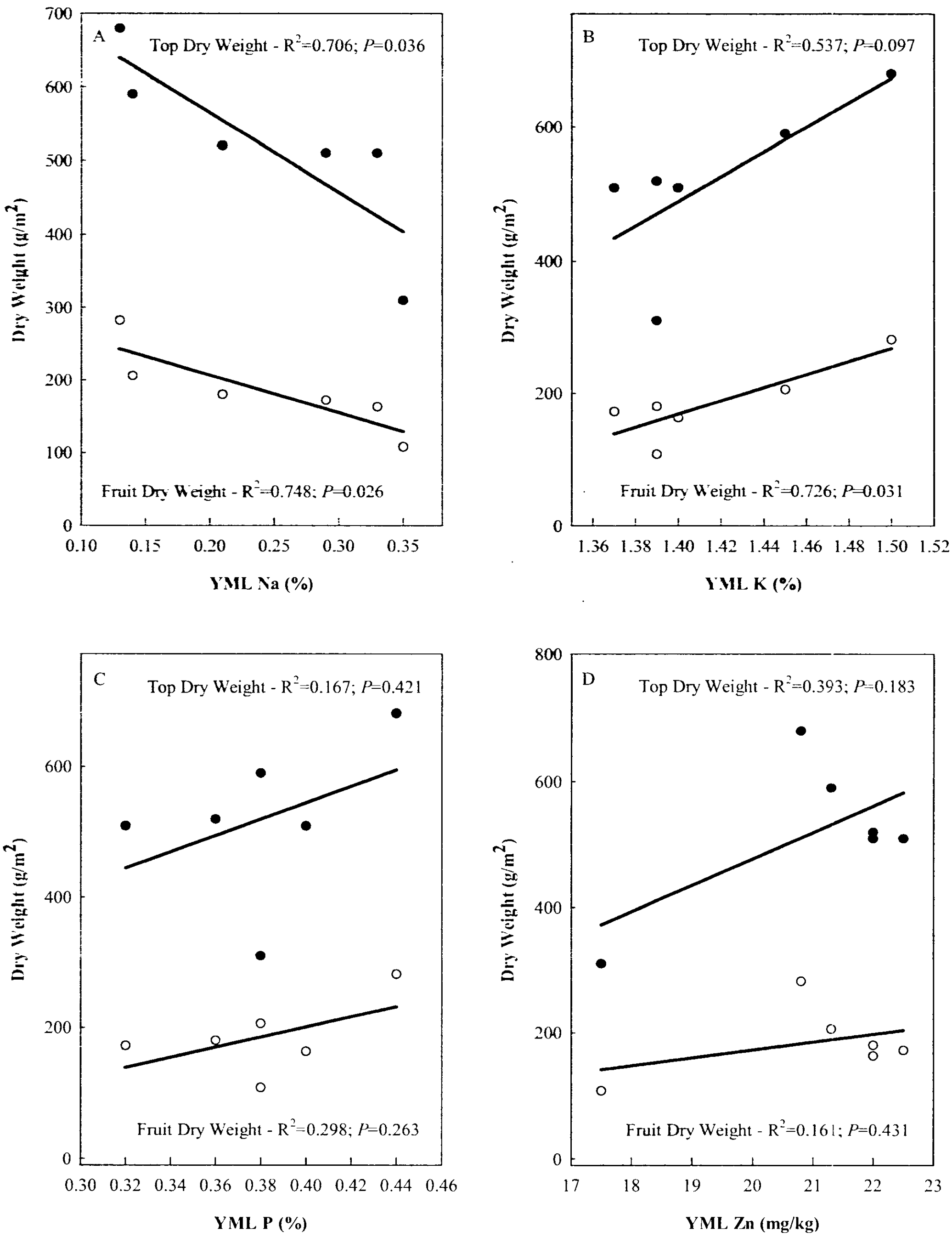
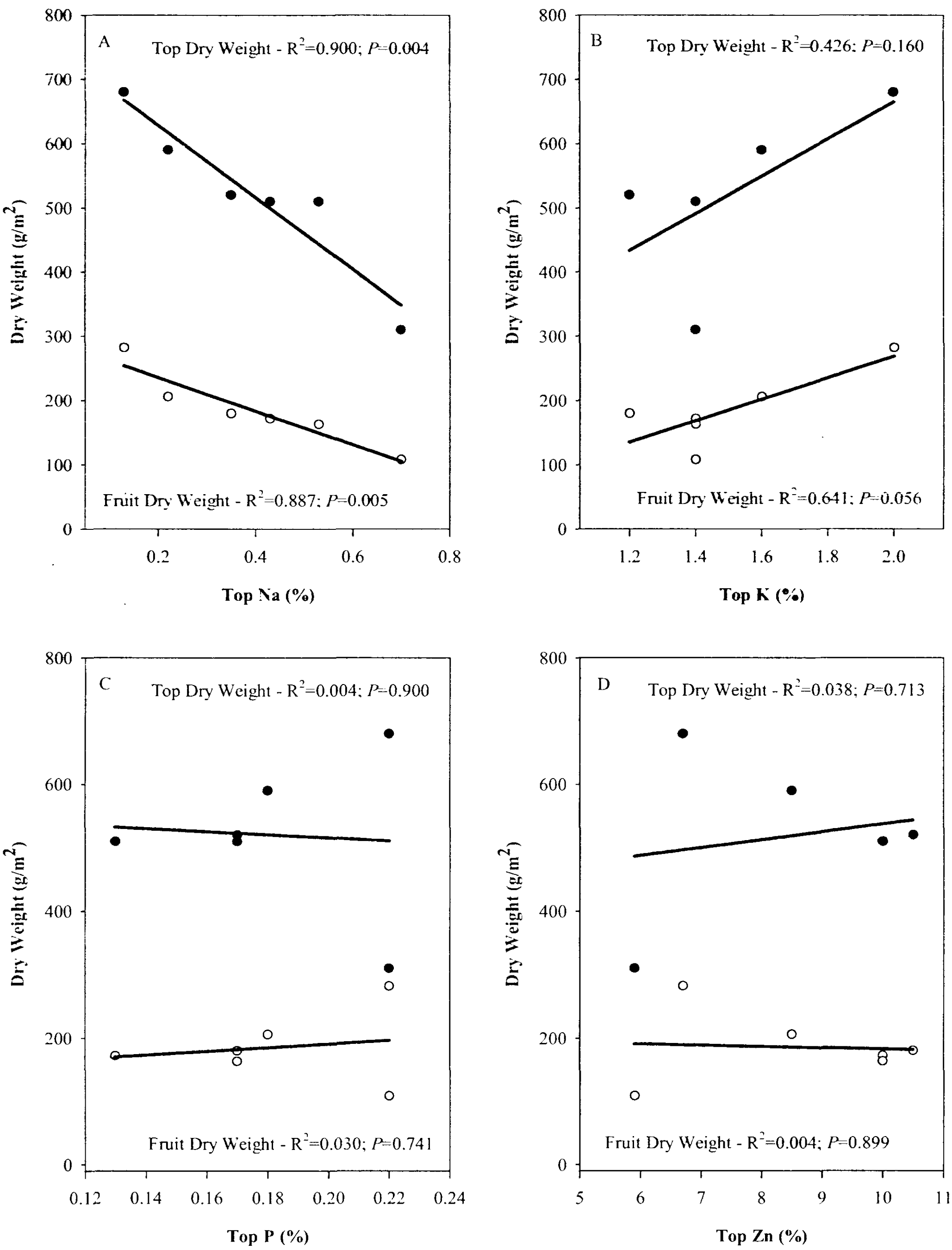


Figure 2-15 A to D The relationships between the top sodium, potassium, phosphorus and zinc concentrations of commercially produced cotton (*Gossypium hirsutum* L.) and the dry matter accumulation and fruit production at harvest. Values are means of four replicates.



Chapter 3. Method development and validation

This chapter describes the development of two methods that were subsequently used in the soil-based glasshouse experiments of Chapters 5 and 6. The first method described is the production of significant quantities of soils (10 to 100s of kg) of variable sodicity from one original non-sodic soil. The second method described is the treatment of soil with polyacrylamide (PAM) to separate the effects of the physical and chemical characteristics of sodic soils on cotton growth and nutrition. A number of experiments tested the efficacy of these methods and the validity of the assumptions necessary for their use in subsequent experiments.

Method 1: The production of soils with a range of sodicity levels

3.1. Introduction

Soil variability between different sites and down the profile makes it difficult to separate the effects of sodicity on crop growth and nutrition from that of other soil properties. These properties include clay mineralogy, soil texture, nutrient status, salinity and organic matter content. Previous investigations into the mechanisms behind declining crop performance in sodic soils using naturally-occurring soils of varying exchangeable sodium percentage (ESP), either in the field or in a glasshouse situation, can therefore be confounded. In order to isolate the effects of sodicity on plant growth and nutrition, it is necessary to produce soils of varying ESP from one soil, minimising the risk of other soil properties confounding the experiment.

Many authors have produced soils of varying ESP from one soil by adding Na salts e.g. $NaHCO_3$ or NaCl (Chang and Dregne 1955; Debnath and Datta 1974; Prasad *et al.* 2003; Wright and Raiper 2000). This methodology has limitations, as the Na salts increase salinity, unless the excess salt is leached from the soil. This is especially true for the high Na applications required to create a strongly sodic clay soil (ESP >15%). The presence of carbonates can also be partially responsible for the rise in soil pH associated with sodic soils (Cruz-Romero and Coleman 1975). Thus, using carbonate salts to vary soil sodicity can confound sodicity with unnaturally high soil pH.

This chapter describes a method to produce soils of variable sodicity from one original soil. The method involves the equilibration of large soil volumes with solutions varying in sodium adsorption ratio (SAR), followed by the removal of excess salt with solutions of similar SAR but lower ionic strength. The resultant soils have predominantly similar properties in all respects that are independent of ESP. This method can minimise the confounding of sodicity with other soil properties in glasshouse experiments.

3.2. Methods

3.2.1. *Soil sodification*

The soil was collected to a depth of 15 cm from a cotton field at the Australian Cotton Research Institute, Myall Vale, NSW (150°E, 30°S), where it had been used for irrigated cotton and wheat cropping for approximately 25 years. The soil was a fertile dark greyish brown cracking clay, classified as a fine, thermic montmorillonitic Typic Haplustert (Soil Survey Staff, 2003) or a Grey Vertosol (Isbell 1996). Selected soil properties are presented in Appendix 1.

The initial sodification method employed was a modified version of the method of Patruno *et al.* (2002). To produce soil with four levels of sodicity, approximately 1000 kg of soil was air-dried, passed through a 10 mm sieve to remove large particles of organic matter and separated into four equal portions. For each sodification treatment, a 250 kg portion was then divided between several calico lined stainless steel trays (30×80×7.5 cm) with perforated bases, each filled to a depth of approximately 5 cm. The trays were designed to allow treatment solution but not soil material to pass through the base. The soil trays were immersed into treatment solutions placed in large stainless steel trays, such that approximately 1 cm of treatment solution covered the soil surface. Each tray was immersed for 4 h, allowed to drain for 1h and then partially dried in a fan-forced oven at 40°C overnight (~12 h). The immersion, drainage and drying cycle was repeated six times. The sodification treatment solutions varied in SAR. The major nutrient cations Ca, Na, Mg and K were included as Cl salts. The first equilibration solution applied had an SAR of 45, as utilised by Kopittke *et al. (2005)*. They observed that soil ESP plateaued with increasing solution Na concentrations at approximately this SAR value using a variety of clay minerals; their method allowed close to complete equilibration of small quantities of soil and solution, via end-over-end tumbling and centrifuging. However, the resultant soil ESP using a solution SAR of 45, under this new sodification method, was only 13% (Table 3-1). Vertosols used for row crop production in northern NSW and southern QLD normally range in ESP from approximately 2 to 25% in the top 90 cm of their profiles (Dang *et al.* 2004; Norrish *et al.* 2001; Rochester Unpublished), indicating that far less than complete equilibration of the soil and solution occurred in the new sodification procedure. This low efficiency of the equilibration probably resulted from the high soil: solution ratio and the lack of agitation of the soil and salt solution.

Richards (1954) described the relationship between solution SAR and soil ESP as follows;

$$\mathrm{ESP} = \frac{100 \times (-0.0126 + 0.01475 \times \mathrm{SAR})}{1 + (-0.0126 + 0.01475 \times \mathrm{SAR})}$$

Using this equation it was anticipated that the 45 SAR treatment would result in an ESP of 40% but rather, under our sodification method, the ESP was measured was only 13 %. This was calculated to correspond to approximately 33% equilibration. Hence, based on this assumption, the SAR treatments required to achieve the targeted range of ESP values were calculated (Table 3-1).

Table 3-1 The sodium absorption ratios, cation concentrations and target soil exchangeable sodium percentage values of the equilibrating solutions.

Treatment	Solution SAR	Na (mM)	Ca (mM)	Mg (mM)	K (mM)	Target ESP (%)
1	0	0.0	8.2	0.28	0.077	2.4
2	45	25.0	0.0	0.31	0.077	12.9
3	100	58.3	0.0	0.34	0.077	19.6
4	200	121.5	0.0	0.37	0.077	24.6

Following equilibration with the four different SAR solutions, the salinity of the soils was adjusted to a level of 2.7 dS/m. At this EC_{se} value soils are considered non-saline and the growth of moderately salt-tolerant plants is not affected (Richards 1954). Consequently, salt was added to some treatments and removed from others. Treated soil was immersed in solutions containing the same K and Mg concentrations as the equilibrating solutions, but using solution Ca and Na concentrations as outlined in Table 3-2. Each soil was submerged six times, for 5 mins and allowed to drain for 1 h between each immersion. The target EC_{se} was set by reducing the EC_{se} of treatment 4 with a solution SAR of zero, which produced the lowest EC_{se} achievable in the most sodic soil. The Ca and Na concentrations required to obtain this EC_{se} in the other treatments were determined by analysing small amounts of the soil.

The soils were then air-dried, mixed and sub-sampled by repeated quartering and prepared for chemical analysis.

Table 3-2 The cation concentrations of the solutions used to adjust the electrical conductivity of the soils.

Treatment	Solution SAR	Na (mM)	Ca (mM)	Mg (mM)	K (mM)
1	0	0.0	14.0	0.28	0.077
2	35	20.0	0.0	0.31	0.077
3	15	8.8	0.0	0.34	0.077
4	0	0.0	0.0	0.37	0.077

3.2.2. *Chemical analysis*

A sample of each soil was ground to pass through a 2 mm sieve. Cation exchange capacity (CEC) determination can be time-consuming and costly and thus it is not often directly measured. Instead, an effective cation exchange capacity (ECEC) is calculated based upon the quantities of exchangeable Ca, Mg, K and Na in the soil. The ECEC and cation concentrations of each soil were analysed using a modified version of the method outlined by Tucker (1972), as this method minimises the impact of soil carbonate on exchangeable Ca determination. A 2 g sample of each soil was weighed into a plastic centrifuge tube and 40 mL of 1 M NH_4Cl (buffered to pH 8.5) was added. The tubes were shaken end-over-end for 1 h, centrifuged for 15 min at 3000 rpm (2010 *g*) and the supernatant filtered using Whatman No.1 paper and analysed for Ca, Na, K and Mg concentration using inductively coupled plasma atomic emission spectroscopy (ICPAES).

Corrections for soluble salts were made according to the method of So *et al.* (2004), rather than using an ethanol pre-wash. A 150 g sample of the soil was raised to field capacity with de-ionised water, covered with wet paper towelling and allowed to equilibrate for 48 h in a closed container. The soil solution was extracted by centrifuging the soil for 30 min at 4000 rpm (3580 g), filtered to 0.22 µm (Millipore Pty Ltd) and Ca, Na, K, Mg and micronutrient concentrations determined using ICPAES. Exchangeable cations were calculated as the difference between the NH_4Cl-extracted cations and soil solution cations.

Additionally, the P content of the soil solutions were analysed using the method outlined by Motomizu *et al.* (1980). A 1 mL aliquot of malachite green reagent was added to 3 mL of each soil solution, the colour allowed to develop for 3 h and the P concentration measured using a spectrophotometer set at 630 nm.

The pH and EC of the soils were analysed in a 1:5 water suspension. An additional analysis of pH was carried out in a matrix of Na and Ca added as chloride salts, in quantities to produce concentrations similar to that found in the soil solution. The $EC_{1:5}$ values were converted to the electrical conductivity of the saturated extract (EC_{se}) using a conversion factor for heavy clays of 5.8 (Slavich and Petterson 1993), to assist the interpretation of the results in terms of plant growth thresholds.

3.2.3. *Statistical analysis*

Analyses of variance (ANOVA) were used to test the significance of treatment differences (P<0.05), with equilibration solution SAR as the factor and three replicate soils per treatment. Statistical analyses were carried out using the Genstat program (7th Edition, Lawes Agricultural Trust) (Payne 1987). The relationship between treatment solution SAR and soil ESP was described using a non-linear regression, fitted using Sigmaplot 7th Edition (SPSS Inc.).

3.3. Results and discussion

3.3.1. *Nutrient concentrations*

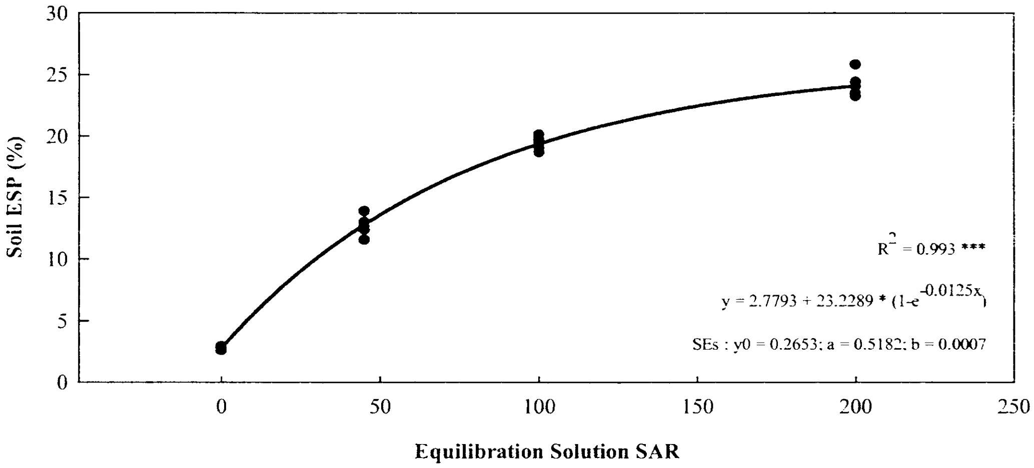
The sodification method had no significant effect on the ECEC of the soil (P=0.23) but increased the Na concentration of the soil (P<0.001) from 2 to 24% and decreased the exchangeable Ca (P<0.001) from 71 to 52% (Table 3-3). This indicates that exchangeable Ca was replaced with exchangeable Na. The sodification method had no significant effect on the exchangeable K concentration of the soil (P=0.36) but the Mg concentration decreased from 22% to 20% (P<0.001) from SAR 0 to SAR 200. These results indicate that the K concentrations remained constant but that small changes in the Mg concentrations of the equilibrating solutions may further minimise differences in the resultant soil.

Table 3-3 The effect of equilibration solution sodium absorption ratio on the effective cation exchange capacity, cation content, pH and EC_{se} of a Grey Vertosol. Values are means of three replicates ± standard errors.

SAR	ECEC ($cmol_c\ kg^{-1}$)	Ca ($cmol_c\ kg^{-1}$)	Na ($cmol_c\ kg^{-1}$)	K ($cmol_c\ kg^{-1}$)	Mg ($cmol_c\ kg^{-1}$)	pH (H_2O)	pH (Soil Solution)	EC_{se} (dS/m)
0	40.8 ± 0.2	29.0 ± 0.2	1.1 ± 0.02	1.6 ± 0.10	9.1 ± 0.2	7.6 ± 0.03	7.3 ± 0.03	2.7 ± 0.2
45	40.8 ± 0.1	25.4 ± 0.1	5.2 ± 0.1	1.5 ± 0.04	8.8 ± 0.1	8.2 ± 0.04	7.6 ± 0.03	2.7 ± 0.3
100	41.4 ± 0.2	23.4 ± 0.2	8.1 ± 0.1	1.5 ± 0.02	8.4 ± 0.1	8.5 ± 0.06	7.8 ± 0.02	2.8 ± 0.2
200	40.8 ± 0.4	21.2 ± 0.2	9.8 ± 0.2	1.5 ± 0.02	8.3 ± 0.1	8.7 ± 0.05	7.9 ± 0.03	2.8 ± 0.1

Vertosols under cropping in Australia commonly range in ESP from 2 to 25 (Dang *et al.* 2004; Norrish *et al.* 2001; Rochester Unpublished) and thus this is an appropriate range for experimental soils. It would be difficult to produce a non-saline sodic soil with an ESP significantly greater than 25%, using the method outlined here and this soil, as the increase in ESP slowed with each increment in solution SAR (Figure 3-1). This pattern is consistent with the results achieved by Kopittke *et al.* (2005) who observed that the increase in soil ESP with increasing concentrations of Na plateaued at a solution SAR of approximately 45, across a variety of clay mineral types. The solution SAR required to obtain the maximum ESP in the revised sodification method is greater than that described by Kopittke *et al.* (2005), due to low efficiency of equilibration of the solution and soil.

Figure 3-1 The resultant exchangeable sodium percentage of a Grey Vertosol subjected to equilibration solutions of varying sodium absorption ratios.



The response of soils to equilibration solution SAR will vary with soil texture and clay mineralogy (Kopittke *et al.* 2005). For this method to be applied to other soils, it may be necessary to either increase or decrease the range of equilibration solution SARs, according to the target ESP and individual soil characteristics.

3.3.2. *pH and EC*

The final leaching solutions produced soils with EC_{se} values approximately equal to the target of 2.7 dS/m (Table 3-3) and differences between the EC values of the different SAR treatments were not statistically significant (P=0.12). Increasing ESP also significantly increased soil pH (P<0.001) (Table 2-4), which rose from 7.6 to 8.7 in water and from 7.3 to 7.9 where soil solution Na and Ca concentrations were matched, as the soil ESP increased from 2 to 24% (Table 3-4). The principal cause of the alkaline pH values of sodic Grey Vertosols is the precipitation of carbonates (Guerrero-Alves *et al.* 2002). In this sodification method, when the soil Ca was exchanged for Na, calcite precipitated, raising soil pH. The soil used in this experiment was slightly calcareous (Appendix 1) and it is likely that the precipitation of calcite contributed to the rise in pH in this soil. The impact of our sodification method on soil pH will vary according to the soil used, but an increase in pH is inevitable in calcareous soils

The inevitable elevation of pH when increasing sodicity in calcareous soils has implications for nutrient availability to plants. Alkaline soils are associated with micronutrient deficiencies, including iron, manganese, boron, copper and zinc (Curtin and Naidu 1998). Therefore, the rise in soil pH may affect plant nutrition and must be acknowledged when investigating crop performance in these soils.

This revised sodification method compares favourably with those described in previous publications, in terms of minimising the confounding of sodicity with salinity and extremes of pH. It is difficult to judge the results of various sodification methods when used on different soils but general comparisons can be made. For example, Wright and Raiper (2000) used $NaHCO_3$ salt to sodify a clay loam; they raised the soil ESP from 1 to 38% but also increased EC_{se} from 1.8 to 6.1 and pH (1:5 soil: water) from 6.3 to 8.7.

3.3.3. *Soil solution nutrient concentrations*

The sodification method also affected the soil solution cation concentrations, as there was a decrease in soil solution Ca ($P<0.001$), K ($P<0.001$) and Mg concentrations ($P<0.001$) and an increase in soil solution Na concentrations ($P<0.001$) with increasing soil ESP (Table 3-4). The nature of cation exchange reactions influences the distribution of nutrients between the soil solution and exchange sites. The soil solution cation concentration data illustrates the tendency for Na to become dominant in the soil solutions of highly sodic soils, creating the extreme ratios of Na:Ca and Na:K that have been implicated in nutritional imbalances (Naidu *et al.* 1996). There was also a sharp decline in the soil solution Mg concentrations with increasing soil solution Na concentrations, but Mg deficiency is rarely reported in cotton crops produced in Grey Vertosols (Rochester *et al.* 1998).

Table 3-4 The effect of equilibration solution sodium absorption ratio on the soil solution cation contents, sodium absorption ratios and phosphorus concentrations of a Grey Vertosol. Values are means of three replicates ± standard errors.

SAR	Soil Solution Nutrient Data					
	Ca (mM)	Na (mM)	K (mM)	Mg (mM)	SAR	P (μM)
0	10.4 ± 0.4	3.9 ± 0.1	0.8 ± 0.0	5.1 ± 0.2	1.4 ± 0.1	0.11± 0.01
45	3.6 ± 0.1	20.8 ± 0.9	0.4 ± 0.0	1.6 ± 0.1	12.9 ± 0.6	0.12 ± 0.01
100	3.4 ± 0.2	39.0 ± 0.0	0.4 ± 0.1	1.5 ± 0.0	24.8 ± 0.4	0.14 ± 0.01
200	2.2 ± 0.1	54.8 ± 0.7	0.3 ± 0.0	1.1 ± 0.1	42.4 ± 0.4	0.18 ± 0.01

The P concentrations of the soil solutions increased with increasing SAR of the equilibration solution ($P<0.001$; Table 3-5). This is consistent with the increased availability of P in sodic soils observed by Curtin *et al.* (1992a) and Gupta *et al.*(1990), due to the dissolution of Ca-P compounds and the release of sorbed P. Despite increased P availability, P deficiency is commonly reported in crop plants produced on sodic soils (Curtin and Naidu 1998; Naidu and Rengasamy 1993). Importantly, potential limitations in crop P uptake in the sodic soils created by this sodification method are more likely due to soil physical or plant factors, rather than the chemical availability of the nutrient, given the measured increase in soil solution P concentrations.

The concentrations of the micronutrients B, Cu, Fe, Mn, Mo and Zn in the soil solutions were significantly lower than the detection limits for the ICPAES. Thus, conclusions cannot be drawn regarding the effect of sodicity on soil solution micronutrient availability.

3.4. Summary

The method outlined in this chapter was employed to create soils varying in ESP from 2 to 24% from a single Grey Vertosol, for later use in glasshouse experiments. There were differences in the resultant soils, in terms of their Mg concentrations, however these differences are only small and could likely be further minimised with small changes in the nutrient concentrations of the equilibrating solutions. Importantly, the major changes in the ionic composition of the soils were that Ca was substituted for Na. The soil properties of pH and solution P concentrations naturally increased as the ESP of the soil rose and thus their effect on plant performance is important to acknowledge in the interpretation of any subsequent results. This method will allow reasonable conclusions to be drawn regarding the direct effects of sodicity on crop growth without the presence of confounding increases in salinity and extreme increases in soil pH.

Method 2: The treatment of soil with polyacrylamide

3.5. Introduction

Sodicity causes structural deterioration of the soil, reducing hydraulic conductivity and increasing susceptibility to surface crusting, hard setting and waterlogging (Levy *et al.* 1998). These factors can limit plant productivity and alter nutrient uptake by reducing seedling emergence and root growth. Sodic soils can also have low redox potential, high soil pH and high soil solution Na concentrations (Curtin and Naidu 1998). These factors can limit plant productivity and alter nutrient uptake by changing nutrient availability to plant roots. A combination of both the physical and chemical impacts of sodicity induces nutrient deficiencies and toxicities in plants (Curtin and Naidu 1998). In order to better understand this issue, there is a need to quantify the relative contribution of the physical and chemical aspects of sodicity to nutrition problems in crop plants. To separate these factors, polyacrylamide (PAM) was added to a Vertosol to attempt to remove the soil physical constraints imparted by soil sodicity without significantly affecting the chemical fertility of the soil in a glasshouse experiment.

A number of authors (Allison 1956; Bernstein and Pearson 1956; Carr and Greenland 1975; Chang and Dregne 1955; Wright and Raiper 2000) utilised synthetic soil conditioning agents, such as vinyl acetate-maleic acid copolymer and PAM to ameliorate the soil structure of sodic soils in pot experiments and improve crop growth. PAM is an anionic linear copolymer of acrylamide and sodium acrylate that is commonly used in irrigated agriculture for improving water infiltration and reducing soil erosion and runoff. PAM has been shown to improve the structure of sodic soils, increase the percentage of water stable aggregates and hydraulic conductivity and reduce surface crusting (Wallace *et al.* 1986a). PAM is attracted to the surface of the soil via van der Waals and coulombic forces, where it increases particle adhesion through flocculation (Sojka and Surapaneni 2000). It is unclear however, whether PAM application may change nutrient availability and soil water retention characteristics (Falatah 1998; Wallace *et al.* 1986b).

In this chapter, an experiment is reported, in which various amounts of PAM were applied to overcome structural problems in sodic soils. Soil structural measurements allowed the determination of the effects of PAM amendment on the physical condition of sodic and non-sodic soils. In situ sampling and analysis of the soil solutions also allowed a comparison of ion concentrations in the soil solution following amendments with PAM. Together, the results of these experiments indicated that the addition of PAM to sodic soils is a suitable method of overcoming the effects of sodicity on soil physical characteristics in a pot experiment. The consistent physical condition of the PAM-amended soils across a range of ESP values means that it is possible to assess the effects of sodic soil chemistry on plant performance, through a comparison of plant responses to varying sodicity treatments in PAM-amended soils. It is also possible to assess the effects of the combined physical and chemical characteristics of sodic soils on plant performance through a comparison of plant responses to the varying sodicity treatments in unamended soils. The slight effect of PAM on the physical fertility of the non-sodic soil and on the availability of P however, means that caution must be employed when attributing differences in plant performance between the control and PAM-amended soil directly to soil physical fertility.

3.6. Methods

3.6.1. *The effect of PAM on the physical condition of non-sodic and sodic soils*

The soil utilised in this experiment was taken from the bulk samples created according to the method outlined above. Repeated quartering separated a 20 kg soil sample of each sodicity treatment. This sample was thoroughly mixed and divided into two equal sub-samples. One sub-sample of each sodicity treatment was spread out in a large stainless steel tray and a solution of PAM was applied at a rate of 0.25% (w/w). The soil was allowed to air dry.

The efficacy of PAM at improving the physical condition of the soils was examined through the analysis of the water-stable aggregates (WSA), mean weight diameter (MWD) and saturated hydraulic conductivity of the soils and through an analysis of the pattern of distribution of water throughout the soil profiles. The WSA and MWD of the soils were determined using a modification of the Yoder wet sieving method (Whitbread 1996). A set of five 100 mm diameter sieves with 125, 250 500, 1000 and 2000 μm mesh screens were used. A 15 g sample of air-dry soil was placed on the top of the sieves and immersed in distilled water at 22°C for 30 s before being sieved for 10 min through a 17 mm amplitude at 30 cycles/min. The sieves were drained and dried at 40°C for 24 h before weighing. The WSA of the soils were then calculated as the percentage of the soil aggregates > 125 μm and the MWD of the soils were calculated as the average diameter of the retained soil aggregates.

Further verification of the efficacy of PAM at achieving uniform physical condition across the range of sodicity treatments was determined using a modification of the mini tension infiltrometer method (Method 510.05) outlined by McKenzie *et al.* (2002b). Cores of soil, 10 cm in both height and diameter were taken from the control and PAM treatments of the 2% and 24% ESP soils and transported to the laboratory untrimmed. These cores were immersed in a water bath by gradually increasing the water level. A sand bed was placed in a water bath and then placed inside a larger tray to allow excess water to overflow. The tension in the infiltrometer was set to equal the surface tension of the sand bed, by setting the infiltrometer to almost bubble when placed directly on the sand bed. The cores were placed on the sand bed and the mini tension infiltrometer filled with deionised water and placed on top of the core. The mini tension infiltrometer was allowed to drain before being refilled and the constant outflow rate measured periodically.

The effect of PAM on the distribution of water in the soil profile was determined by placing air dry soil from the control and PAM treatments of the 2% ESP soil and PAM treatment of the 24% ESP soils in cores 10 cm in diameter, 75 cm in height and sealed at the base. Each core was wet by weight to field capacity, covered with a plastic bag and allowed to equilibrate for 24 hr. The soil in each core was then separated into 10 cm increments and its oven-dried gravimetric water content determined.

3.6.2. *The effect of PAM on chemical nutrient availability*

A sodic and a non-sodic soil were used in this experiment. The characteristics of these soils are outlined in Table 3-5.

Table 3-5 Characteristics of the Grey Vertosols used in the experiment to determine the effect of polyacrylamide on nutrient availability.

Treatment	Collection Site	Crop Rotation	Clay[b] (%)	pH[b]	EC_{se}[c] (dS/m)	CEC[d] (cmol/kg)	ESP (%)	Colwell P[f] (mg/kg)
Non-Sodic	'ACRI' Narrabri	Cotton-Cereal	52	8.1	0.7	42.0	2.1	42
Sodic	'Mirrabooka ' Narrabri	Cotton-Cereal	59	6.3	3.6	58.2	17.0	11

[a] Isbell (1996); [b]dispersion and sedimentation; [c]1:5 soil: solution ratio in H_2O; [d]saturation extract; [e]1 M NH_4Cl; [f]Colwell (1966)

The effects of PAM on the availability of nutrients in each of the soils were determined through the analysis of the composition of the soil solutions. Four replicates, each consisting of 600 g of soil, were placed in pots of 7 cm diameter and 15 cm height and the base of each pot was sealed with a plastic bag. One soil solution sampler was placed centrally in each pot. Deionised water was added to bring the soils to the previously determined field capacity of 42% (w/w) and allowed to equilibrate for 24 h. Soil solution was extracted using a modified version of the method outlined by Menzies and Guppy (2000) using polyacrylonitrile, ultrafiltration hollow fibres. Soil solution collected in this way differs slightly from that obtained by centrifugal drainage methods as only solution from within the larger pores is extracted (Menzies and Guppy 2000). Soil solution cation and P concentrations were determined using ICPAES whilst anion concentrations were determined using ion chromatography (IC) (Dionex ICS2000).

3.6.3. *Statistical analysis*

Analyses of variance (ANOVA) were used to test the significance of treatment differences ($P<0.05$). In the WSA, MWD and hydraulic conductivity analyses soil sodicity and PAM amendment were the factors and there were three replicate soils per treatment. Where significant interactions between the effects of sodicity and the effects of PAM amendment were found, differences between individual treatment combinations were further evaluated by least significant difference (LSD) ($P<0.05$) and these values used to inform the labelling of the tables of results with indicators of significance. The water distribution and soil solution composition analyses were carried out separately in the non-sodic and sodic soils, with PAM as the factor and three replicate soils per treatment. Statistical analyses were carried out using the Genstat program (7^{th} Edition, Lawes Agricultural Trust) (Payne 1987).

3.7. Results

3.7.1. *The effect of PAM on the physical condition of non-sodic and sodic soils*

There were significant interactions between the effects of sodicity and the effects of PAM on soil structure (P<0.001). The WSA and MWD of the soils were negatively affected by soil sodicity in the control treatments (P<0.001), but there were no effects of sodicity on the WSA or MWD of the PAM-amended soils (Table 3-6). Addition of PAM had no significant effect on the WSA of the non-sodic soil but increased the WSA of all of the sodic soils. Addition of PAM had a positive effect on soil structure, improving the MWD at all ESP levels to approximately 1200 µm. In the non-sodic soils, the increase in MWD that occurred as a result of PAM application was 894 µM. In the 24% ESP soils, the increases in WSA and MWD that occurred as the result of PAM application were 57% and 1094 µM respectively.

Table 3-6 The effect of sodicity and polyacrylamide treatment on the water stable aggregation and mean weight diameter of a Grey Vertosol. Values are means of three replicates ± standard errors. Within columns, means that do not share a common superscript letter are significantly different (*P*=0.05) and ns designates no significant interaction between the effects of sodicity and the effects of waterlogging.

PAM Treatment	ESP (%)	Water Stable Aggregates (%)	Mean Weight Diameter (mm)
Control	2	85.7 ± 5.7 ^{a}	0.4 ± 0.0 ^{a}
	12	65.3 ± 3.2 ^{b}	0.2 ± 0.0 ^{b}
	19	50.0 ± 4.0 ^{c}	0.2 ± 0.1 ^{b}
	24	33.0 ± 2.9 ^{d}	0.2 ± 0.2 ^{b}
PAM	2	90.6 ± 1.1 ^{a}	1.3 ± 0.0 ^{c}
	12	90.0 ± 1.6 ^{a}	1.4 ± 0.0 ^{c}
	19	90.5 ± 1.7 ^{a}	1.3 ± 0.1 ^{c}
	24	90.1 ± 1.3 ^{a}	1.3 ± 0.1 ^{c}
LSD		*5.8*	*0.1*

There was a significant interaction between the effects of sodicity and the effects of PAM on the saturated hydraulic conductivity of the soil ($P<0.001$). Application of PAM significantly reduced the hydraulic conductivity of the non-sodic soil and increased the saturated hydraulic conductivity of the sodic soil ($P<0.001$) (Table 3-7). There was no significant difference in the hydraulic conductivity of the PAM amended non-sodic and sodic soils. The treatment of the non-sodic soil with PAM did not alter the distribution of water in the profile upon wetting ($P>0.05$) and there was no significance effect of sodicity on the distribution of water in the profiles of the PAM-amended soils ($P>0.05$) (Table 3-7).

Table 3-7 The effect of sodicity and polyacrylamide treatment on the hydraulic conductivity of a Grey Vertosol and the effect of polyacrylamide treatment on the distribution of water in the soil profile of a non-sodic Grey Vertosol. Values are means of three replicates ± standard errors. Within columns, means that do not share a common superscript letter are significantly different ($P=0.05$).

ESP (%)	PAM Treatment	Hydraulic Conductivity (mm/hr)	Distribution of Water in the Soil Profile				
			Water (%) (0-10cm)	Water (%) (10-20cm)	Water (%) (20-30cm)	Water (%) (30-40cm)	Water (%) (40-50cm)
2.8	Control	15.4 ± 1.2 ^{a}	40.7 ± 0.9	38.9 ± 0.1	39.0 ± 0.4	39.2 ± 0.9	39.2 ± 0.6
	PAM	4.1 ± 0.7 ^{b}	42.4 ± 0.4	39.0 ± 0.4	38.9 ± 0.1	38.3 ± 0.2	39.6 ± 0.4
24.1	Control	0.0 ± 0.0 ^{c}	N/A	N/A	N/A	N/A	N/A
	PAM	4.1 ± 0.6 ^{b}	42.1 ± 0.7	41.1 ± 0.3	39.3 ± 0.1	38.6 ± 0.1	38.4 ± 0.4
LSD		*2.9*	*N/A*				

3.7.2. *The effect of PAM on soil solution composition*

Addition of PAM to non-sodic and sodic Grey Vertosols in increasing proportions had no significant effect on the soil solution concentrations of the measured cations or anions ($P>0.05$), with the exception of soil solution P (Table 3-8 and Table 3-9). As the amount of PAM applied to the soil increased, there was significant decrease in the P concentrations in the soil solution ($P=0.04$). In the sodic soil, the P concentration was below the detection limit of the IC, even without the addition of PAM.

Table 3-8 The effect of polyacrylamide on soil solution cation concentrations in a sodic and non-sodic Grey Vertosol. Values are means of four replicates ± standard errors.

Soil	PAM Treatment (% w/w)	Soil Solution Nutrient Concentrations				
		Ca (mM)	Mg (mM)	Na (mM)	K (mM)	Zn (µM)
Non-Sodic	0	7.1 ± 0.5	0.3 ± 0.03	1.3 ± 0.1	0.2 ± 0.01	0.2 ± 0.04
	0.0005	7.7 ± 0.4	0.4 ± 0.03	1.5 ± 0.1	0.2 ± 0.01	0.2 ± 0.02
	0.001	7.2 ± 0.8	0.4 ± 0.04	1.5 ± 0.1	0.2 ± 0.01	0.1 ± 0.02
	0.25	11.4 ± 2.9	0.6 ± 0.10	1.9 ± 0.2	0.2 ± 0.02	0.4 ± 0.20
Sodic	0	9.9 ± 2.9	0.7 ± 0.2	8.8 ± 1.4	0.1 ± 0.02	0.2 ± 0.04
	0.0005	11.5 ± 3.9	0.8 ± 0.2	9.3 ± 1.7	0.1 ± 0.02	0.2 ± 0.06
	0.001	7.3 ± 1.4	0.5 ± 0.1	7.9 ± 0.7	0.1 ± 0.01	0.3 ± 0.09
	0.25	8.8 ± 2.4	0.6 ± 0.2	8.8 ± 1.2	0.1 ± 0.01	0.3 ± 0.08

Table 3-9 The effect of polyacrylamide on soil solution anion concentrations in a sodic and non-sodic Grey Vertosol. Values are means of 4 replicates ± standard errors.

Soil	PAM Treatment (% w/w)	Soil Solution Nutrient Concentrations		
		P (µM)	N (mM)	S (µM)
Non-Sodic	0	0.07 ± 0.01	2.9 ± 0.3	0.05 ± 0.02
	0.0005	0.06 ± 0.00	4.5 ± 0.3	0.03 ± 0.00
	0.001	0.06 ± 0.01	4.1 ± 0.7	0.03 ± 0.00
	0.25	0.04 ± 0.01	5.1 ± 1.3	0.04 ± 0.00
Sodic	0	0.00 ± 0.00	6.4 ± 2.1	0.10 ± 0.06
	0.0005	0.00 ± 0.00	7.8 ± 2.4	0.03 ± 0.00
	0.001	0.00 ± 0.00	6.4 ± 1.3	0.01 ± 0.00
	0.25	0.00 ± 0.00	7.4 ± 1.9	0.10 ± 0.04

3.8. Discussion

3.8.1. *The effect of PAM on soil physical condition*

It is important to determine whether the addition of PAM maintains soil physical condition across a range of sodicity levels, in order to attribute any effects of sodicity on plant growth or nutrition in the PAM treatments to soil chemical, rather than physical factors. The WSA and MWD of the PAM-amended soils were not different across the range of sodicity treatments

(Table 3-6) and there was no significant difference in the hydraulic conductivities of the non-sodic and most sodic PAM-amended soils (Table 3-7). Additionally, there was no significant difference in the distribution of water in the profiles of the PAM-amended non-sodic and sodic soils upon wetting (Table 3-7). These results suggest that the application of PAM resulted in soils of equivalent physical condition across the range of sodicity treatments applied. This means that any differences in plant performance can be attributed to chemical effects of sodicity, enabling the physical and chemical effects of sodicity to be distinguished.

It is also important to determine whether the addition of PAM has an effect on the physical condition of the non-sodic soil, in order to attribute any effects of PAM on plant growth or nutrition to soil physical factors at a given sodicity treatment. The addition of PAM to the non-sodic soil had no significant effect on the WSA but increased the MWD. The decreased saturated hydraulic conductivity of the non-sodic soil following the addition of PAM, also indicates that the rate at which water moved through this saturated soil was reduced either directly by the application of PAM or indirectly as a result of the PAM application on soil structure. Lentz (2003) and Malik and Letey (1992) also measured reductions in the saturated hydraulic conductivity of soils amended with anionic PAM, and attributed these reductions to an increased viscosity of soil water in PAM-amended soils, associated with the charge on the PAM material. PAM had no effect on the distribution of water through the soil profile of the non-sodic soil at field capacity however, which indicates that the hydraulic conductivity in the PAM-amended soil was sufficient to allow adequate movement of water through the soil. There was no accumulation of water in either the upper or lower sections of the soil profile and thus PAM did not induce surface or subsoil waterlogging conditions. Together, the MWD and hydraulic conductivity results suggest that the application of PAM altered the physical condition of the non-sodic soil. This effect requires that caution must be employed when attributing differences in plant performance between control and PAM-amended soil directly to soil physical condition.

The reductions in WSA and MWD in this soil with increasing sodicity, when not amended with PAM illustrate the effects of soil Na on soil structure, under non-saline conditions. These reductions in WSA and MWD can be attributed to the slaking and dispersion of the soil aggregates upon wetting. The saturated hydraulic conductivity of the most sodic control treatment was negligible, making this soil highly susceptible to waterlogging. It is possible to assess the implications of sodic soil physical and chemical condition on plant performance through a comparison of plant responses to varying levels of soil sodicity in soils not amended with PAM.

3.8.2. *The effect of PAM on soil solution composition*

This experiment also aimed to identify whether the addition of PAM to soil would affect the chemical availability of nutrients to plants. The addition of increasing proportions of PAM to a Grey Vertosol had no significant effect on the soil solution concentration of major cations and anions in the soil solution. However the exception to this observation concerns soil solution P concentration. In the non-sodic soil P concentrations decreased with the addition of PAM, while in the sodic soil no decrease was observed, because the P concentrations in the sodic soil were very low. The effect of PAM on P availability needs to be acknowledged in the interpretation of the results of subsequent pot experiments.

3.9. Summary

The addition of PAM to soil is an appropriate method to separate the physical and chemical effects of sodic soils on plant growth. The consistent physical condition of the PAM-amended soils across a range of ESP values means that it is possible to assess the effects of sodic soil chemistry on plant performance, through a comparison of plant response to the varying sodicity treatments in the PAM-amended soils. It is also possible to assess the effects of the combined physical and chemical condition of sodic soils on plant performance, through a comparison of plant responses to varying sodicity treatments in unamended soils. The slight effect of PAM on the physical fertility of the non-sodic soil and on the availability of P however, means that caution must be employed when attributing differences in plant performance between the control and PAM amended soil directly to soil physical fertility.

Chapter 4. Reduced growth and premature senescence of cotton in sodic soils: is it due to soil solution chemistry?

4.1. Introduction

Approximately 23% of the Australian landmass (NLWRA 2002) and 80% of the irrigated agricultural area in Australia is occupied by sodic soils (Rengasamy and Olsson 1993). Rengasamy (2001) estimated that more than 50% of soils used for high value crops such as cotton are affected by sodicity. The experiment outlined in Chapter 2 and that carried out by Rochester (Unpublished) reported that cotton crops produced on sodic soils commonly have reduced concentrations of P and K and increased concentrations of Na in their tissues. Despite the prevalence of sodic soils in cotton production systems however, the mechanisms behind these patterns of nutrient accumulation are not fully understood. In order to better understand this issue, there is a need to isolate the effect of high Na concentrations alone on the growth and nutrition of cotton, from the effects of reduced soil physical fertility and elevated soil pH values.

A number of authors have utilised hydroponic experiments to investigate the effect of sodium chloride (NaCl) on cotton growth and nutrition (Cramer *et al.* 1986; Cramer *et al.* 1987; Kent and Lauchli 1985; Kurth *et al.* 1986; Zhong and Lauchli 1993). However these experiments were conducted with seedling plants, over just a few days and the nutrient solutions were not designed to mimic sodic soil solutions. A longer experiment was required to allow effects of solution Na on plant development to be expressed. An experiment with hydroponic solutions based upon soil solution nutrient concentrations was also required to make the results of these previous authors more relevant to cotton field production systems.

This chapter reports such an experiment, in which various Na:Ca ratios and EC levels were used in hydroponics solutions, in order to separate their effects on the growth and nutrition of cotton plants. This knowledge is important from a management perspective because in the field, sodicity and salinity can occur both together and separately and these factors may have separate affects on cotton performance.

4.2. Methods

4.2.1. *Determination of sodic soil solution composition*

The determination of soil solution composition was carried out on a soil collected from a cotton field at the Australian Cotton Research Institute, Myall Vale, NSW (30°S, 150°E), where it had been used for irrigated cotton and wheat cropping for approximately 25 years. The soil was a fertile dark greyish brown cracking clay, classified as a fine, thermic montmorillonitic Typic Haplustert (Soil Survey Staff 2003) or a Grey Vertosol (Isbell 1996). Selected soil properties are presented in Appendix 1.

Soils of four different ESP levels were prepared in 20 kg batches according to the method outlined in Chapter 3 (Section 3.2.1), in order to create soils that varied primarily in their exchangeable Na and Ca content, while maintaining soil properties that are independent of ESP constant. The soil was equilibrated with treatment solutions varying in SAR (0, 45, 100 and 200) and with the major nutrient cations Ca, Na, Mg and K included as Cl salts. Excess salt was removed from each treatment by equilibration of the soil with solutions of equivalent SAR but lower total cation concentration.

The soil solution composition of the various ESP treatments were determined using the method outlined by So *et al.*(2004). A 150 g sample of soil from each sodicity treatment was raised to field capacity with de-ionised water, covered with wet paper towelling and allowed to equilibrate for 48 h in a closed container. The soil solution was extracted by centrifuging the soil for 30 min at 4000 rpm or 3580 g, filtered to 0.22 μm (Millipore Pty Ltd) and nutrient concentrations determined using inductively coupled plasma atomic emission spectroscopy

(ICPAES). Soil solution nutrient levels were then used to determine the hydroponic solution culture composition.

4.2.2. *Nutrient solution m compositions*

Based on the sodic soil solution compositions, nine nutrient solutions were developed, varying in both ionic strength and Na:Ca ratio (Table 4-1). Phosphorus was included in the nutrient solutions at concentrations approximately 10 times those found in the soil to avoid the characteristic saw-toothing pattern associated with low P in hydroponic plant culture. The Na concentrations utilised mirrored those found in the soil solutions of soils with ESP values up to approximately 25%. A maximum ionic strength of 6 dS/m was chosen because it was below the level of 7.7 dS/m, at which ionic strength reduces the growth of cotton (Maas and Hoffman 1977). A maximum Na:Ca of 45:1 was chosen as it allowed the inclusion of the range of Na concentrations found in soils at commonly occurring soil ESP values of 2 to 25% (Dang *et al.* 2004; Norrish *et al.* 2001; Rochester Unpublished), while maintaining adequate Ca concentrations to prevent Ca deficiency (Blair and Taylor 2004).

Table 4-1 Hydroponic nutrient solution calcium and sodium concentrations

Treatment ID	EC (dS/m)	Na:Ca Ratio	Ca (mM)	Na (mM)
1	2.5	0.2	11.5	2.2
2	2.5	3.75	4.0	15.0
3	2.5	46	0.46	20.5
4	4.25	0.2	20.3	3.9
5	4.25	3.75	6.8	24.6
6	4.25	46	0.8	36.8
7	6	0.2	32.7	5.8
8	6	3.75	11.1	41.1
9	6	46	1.2	56.6

Basal macronutrients were applied at the following concentrations (mM) K 0.3; Mg 1.2, P 0.3; S 0.8. Ammonium and nitrate N were applied at 0.03 mM and 5.3mM respectively. Basal micronutrients were applied at the following concentrations (µM) – Fe 65; Cu 28; B 83; Zn 11; Mo 0.7.

The above nutrient treatments were each dissolved in 260 L of distilled water. The pH and EC of the nutrient solutions were measured at least daily with a portable pH and EC meter. The pH values of the nutrient solutions were maintained between 6.2 and 6.8 and small fluctuations in pH were corrected as needed by the addition of NaOH or HCl. Increases in the EC of the solution were corrected by the addition of distilled water. The pH values of the nutrient solutions were largely controlled by the balance of NO_3^- and NH_4^+ ions. The optimum level of NH_4^+ ions needed to stabilise the pH of the solution was found to be approximately 0.5% of total solution N (mM).

Replacement of extracted nutrients was undertaken following analysis of the solution composition on a weekly basis. As plant size increased, estimates of macronutrient usage were used to maintain solution composition mid week.

4.2.3. *Hydroponics Equipment*

A 260 L recirculating flowing solution culture system was established for each of the nine treatments. Each structure was composed of a polyvinyl chloride (PVC) pipe, 15 cm in diameter and 2 m in length. Eight holes of 3 cm diameter were cut in the top of the pipe for the insertion of 4 cotton plants per treatment. The water level in the PVC pipe was controlled with a vertical drilled tube inserted at the end of the PVC pipe, allowing recirculation back to the bulk solution. The water level was maintained 2 cm below the top of the PVC pipe. The bulk of the solution was held in a 220 L plastic container and pumped from this container by an underwater pump into a 20 L plastic container held overhead. A float valve located in the overhead container controlled the flow of solution through the system.

4.2.4. *Plant culture*

This experiment was conducted in a glasshouse at the University of New England, Armidale, NSW Australia. The temperature range of the glasshouse during the experimental period was maintained between 20°C and 35°C.

Seeds of cotton (cv Sicot 289BR, CSD Pty Ltd) were planted individually in small pots filled with a 50:50 mixture of sand and peat. These plants were watered daily and allowed to grow to a height of 8 cm, before being transplanted into the hydroponics system. Plants of uniform size were selected and mounted in the hydroponics system using small plastic cups with holes in the bottom and non-wetting cotton wool to hold them upright. Once a plant height of approximately 30 cm was reached, a trellis was mounted above the hydroponics systems to provide further support. Following a 42-day period of growth in the hydroponics system, the plants were harvested.

4.2.5. *Plant measurements and analysis*

At the appearance of 1st square the youngest mature leaf (YML) was taken from each plant. At harvest the plants were removed from the hydroponics system and rinsed in deionised water before measurements were taken and the plants were separated into YML, roots, tops and fruit. Measurements of plant height, number of nodes, number of fruit, 4-5th top internode length and leaf area were taken. All plant material was dried in a fan-forced oven at 80°C, weighed, ground to <2 mm and digested with perchloric acid and hydrogen peroxide, using the sealed chamber method outlined by Anderson and Henderson (1986). The nutrient composition of the samples was determined using the ICPAES. An Australasian Soil and Plant Analysis Council (ASPAC) plant sample was included in the analysis, in order to ensure the accuracy of the results.

4.2.6. *Root morphology*

Hand sections of plant roots were cut at the point of the emergence of the first lateral and dyed using a 1% solution of toluene blue. The sections were mounted on slides and examined under a light microscope. The dimensions of 6 randomly selected cells from the stele and 6 randomly selected cells from the cortex were measured using the microscope eyepiece micrometer.

4.2.7. *Statistical analysis*

Analyses of variance (ANOVA) were used to test the significance of treatment differences (P<0.05), with EC and Na:Ca ratio as factors (see Table 4-1), and four replicate plants per treatment. Where significant interactions between the effects of nutrient solution EC and Na:Ca ratio were found, differences between individual treatment combinations were further evaluated by least significant difference (LSD) (P<0.05) and these values used to inform the labelling of the tables of results with letters indicating significance. Linear and exponential curves were used to describe relationships between data and were fitted using Sigmaplot 7th Edition (SPSS Inc.). Statistical analyses were carried out using the Genstat program (7th Edition, Lawes Agricultural Trust) (Payne 1987).

In this analysis, each individual plant within a given nutrient solution treatment was designated as a replicate, despite the location of each of the replicates within one hydroponics tube. It was impossible in this experiment to include multiple hydroponics tubes of each nutrient solution treatment, due to glasshouse space and financial limitations. The use of individual plants as replicates was valid in this experiment, as the aim of the experiment was to assess the response of cotton plants to nutrient solution composition. There was no significant effect of plant position within each hydroponics tube on growth or nutrition results and the most significant within-treatment variation in this system was believed to be derived from genetic variation between individual cotton plants. Together these factors validate the use of individual plants as treatment replicates.

4.3. Results

4.3.1. *Soil solution composition*

The results of the soil solution analysis and a similar analysis carried out by Naidu *et al.* (1995) are summarised in Table 4-2. Although nutrient concentrations are similar in the two experiments, the soil solution Na and Ca concentrations in this experiment were higher those observed by Naidu *et al.* (1995). The concentrations of Ca, K, Mg and S in the soil solutions at the different ESP levels are relatively consistent in this experiment, because one Grey Vertosol was used. Greater variation is evident in the analysis undertaken by Naidu *et al.* (1995) because different soils were analysed. In both analyses there is a consistent increase in soils solution Na concentration with increasing soil ESP. An increase in soil solution P with increasing ESP is also evident in this experiment but no such trend is present in the data of Naidu *et al.* (1995).

Table 4-2 Soil solution nutrient concentrations of a Grey Vertosol varying in sodicity and numerous sodic soils after Naidu *et al.* (1995).

Sample Origin	Soil ESP	Soil Solution Nutrient Concentrations (mM)					
		Ca	K	Mg	Na	S	P
Soil Solution Analysis	**2**	3.2	0.2	1.6	3.7	1.1	0.010
	11	2.0	0.2	0.8	20.9	1.1	0.013
	15	3.0	0.2	1.3	35.8	1.1	0.016
	22	4.5	0.3	2.2	50.7	1.1	0.016
(Naidu *et al.* 1995)	**5**	1.4	0.3	0.4	1.6	0.2	0.006
	6	1.1	0.2	0.3	1.8	0.2	0.003
	6	0.3	1.9	0.1	1.7	0.6	0.090
	7	1.7	1.1	1.2	6.0	0.7	0.029
	11	0.3	0.4	0.5	2.9	0.1	0.006
	14	1.3	4.3	1.7	10.6	2.2	0.006

4.3.2. *Plant measurements*

The different hydroponic solutions had little effect on the growth of the plants, with no significant effect of either the Na:Ca ratio or EC on the number of nodes, number of fruit, leaf area, root dry weight or fruit dry weight of the plants across the range of applied nutrient solutions (Table 4-3). Exceptions to this pattern occurred in the cases of plant height, 4-5th internode length and top dry weight. Plant height was significantly reduced by higher nutrient solution EC (P=0.01) and tended to be reduced by increasing nutrient solution Na:Ca concentration ratio (P=0.09). The length of the 4-5th internodes of the plants tended to be reduced by higher nutrient solution Na:Ca concentrations ratio (P=0.06) and EC (P=0.07). The top dry weights of the plants tended to be reduced by higher nutrient solution EC (P=0.09) but nutrient solution Na:Ca was less influential (P=0.40). There was also a significant interaction between the effects of nutrient solution Na:Ca ratio and the effects of EC on plant height (P=0.01) and the cotton plants grown at the highest Na concentration were 21% shorter than the plants in the treatment with the lowest Na concentration.

In addition to the vegetative growth parameters, nutrient solution Na significantly altered root cell growth (Table 4-4). Cotton root diameter was negatively related to nutrient solution Na:Ca ratio and EC (P<0.001). Stele cell area was also negatively related to the Na Ca ratio of the nutrient solution (P<0.001) and positively related to EC (P=0.003). Significant variation was apparent in the cortex cell area measurements (P<0.05) and there was a significant interaction between the effects of nutrient solution Na:Ca ratio and EC on cortex cell area, but these were not related to nutrient solution Na:Ca ratio or EC. The interactions between the effects of nutrient solution Na:Ca ratio and the effects of nutrient solution EC on cotton root width and stele cell area were also significant (P<0.001). The cotton roots in the nutrient solution with the highest Na concentration were significantly thinner at the point of emergence of the first lateral than those in all of the other treatments. Additionally, increasing nutrient solution Na:Ca ratio decreased the stele cell areas of cotton in the 2.5 and 6 dS/m treatments but not in the 4.25 dS/m treatments.

Table 4-3 The effect of solution electrical conductivity, sodium to calcium ratio and sodium concentration on the growth of cotton (*Gossypium hirsutum* L.) in solution culture. Values are means of 4 replicates ± standard errors. Within columns, means that do not share a common superscript letter are significantly different (*P*=0.05) and ns designates no significant interaction between the effects of nutrient solution sodium to calcium ratio and electrical conductivity.

EC (dS/m)	Na:Ca Ratio	Na (mM)	Height (cm)	Nodes (No.)	Fruit (No.)	Leaf Area (cm^2)	Top Dry Weight (g)	Root Dry Weight (g)	Fruit Dry Weight (g)	5^{th} Internode Length (cm)
2.5	**0.2**	**2.2**	80.2 ± 2.0 ^{a}	14.5 ± 0.5	4.5 ± 0.3	43.0 ± 3.5	21.2 + 0.6	5.6 ± 0.5	0.29 ± 0.02	11.6 ± 2.1
2.5	**4**	**15.0**	77.1 ± 0.9 ^{ab}	14.3 ± 0.3	4.5 ± 0.3	46.5 ± 4.9	22.9 + 1.8	6.3 ± 0.6	0.35 ± 0.06	9.7 ± 1.6
2.5	**46**	**20.5**	74.7 ± 1.7 ^{ab}	13.8 ± 0.3	4.0 ± 0.3	40.6 ± 5.6	18.3 + 1.4	6.6 ± 0.2	0.20 ± 0.07	8.9 ± 0.9
4.25	**0.2**	**3.9**	77.3 ± 3.0 ^{ab}	13.8 ± 0.5	4.0 ± 0.4	37.6 ± 2.6	18.6 ± 1.7	5.8 ± 0.5	0.16 ± 0.03	11.0 ± 1.5
4.25	**4**	**24.6**	77.3 ± 2.5 ^{ab}	14.0 ± 0.6	4.0 ± 0.4	37.6 ± 4.2	19.6 + 2.6	5.5 ± 0.6	0.44 ± 0.17	9.3 ± 0.9
4.25	**46**	**36.8**	82.3 ± 4.0 ^{ab}	14.8 ± 0.3	5.5 ± 0.9	42.9 ± 5.6	22.8 + 2.9	6.0 + 0.6	0.41 ± 0.13	10.3 + 0.4
6	**0.2**	**5.8**	77.2 ±1.3 ^{ab}	13.5 + 0.3	3.8 ± 0.5	36.1 ± 3.3	17.2 + 1.6	5.5 + 0.6	0.22 ± 0.07	9.8 ± 1.1
6	**4**	**41.1**	75.1 4.7 ^{b}	14.3 + 0.5	4.0 ± 1.3	38.0 ± 7.4	19.8 + 3.7	5.9 + 0.8	0.32 + 0.12	8.6 + 1.2
6	**46**	**56.6**	63.5 ±2.5 ^{c}	14.0 + 0.7	4.5 ± 0.3	38.6 + 6.0	14.3 + 1.5	5.5 + 0.7	0.28 + 0.09	5.5 + 0.4
LSD			*7.35*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Table 4-4 The effect of solution electrical conductivity, sodium: calcium ratio and sodium concentration on the characteristics of cotton (*Gossypium hirsutum* L.) roots in solution culture. Values are means of 4 replicates ± standard errors. Within columns, means that do not share a common superscript letter are significantly different (P=0.05).

EC (dS/m)	Na:Ca Ratio	Na (mM)	Root Width (cm)	Stele Cell Area (μm^2)	Cortex Cell Area (μm^2)
2.5	**0.2**	**2.2**	1.69 ± 0.02 [b]	1.81 ± 0.14 [bc]	0.73 ± 0.04 [cd]
2.5	**4**	**15.0**	1.84 ± 0.02 [a]	1.54 ± 0.13 [cd]	0.78 ± 0.06 [bc]
2.5	**46**	**20.5**	1.59 ± 0.02 [cd]	1.21 ± 0.08 [d]	0.73 ± 0.05 [cd]
4.25	**0.2**	**3.9**	1.63 ± 0.03 [bc]	1.72 ± 0.15 [bc]	0.89 ± 0.06 [b]
4.25	**4**	**24.6**	1.53 ± 0.02 [d]	1.71 ± 0.14 [bc]	0.69 ± 0.05 [cd]
4.25	**46**	**36.8**	1.61 ± 0.02 [c]	1.84 ± 0.15 [bc]	1.14 ± 0.09 [a]
6	**0.2**	**5.8**	1.70 ± 0.03 [b]	2.39 ± 0.23 [a]	0.91 ± 0.05 [b]
6	**4**	**41.1**	1.59 ± 0.04 [cd]	2.09 ± 0.1 [ab]	0.79 ± 0.04 [bc]
6	**46**	**56.6**	1.21 ± 0.04 [e]	1.31 ± 0.12 [d]	0.67 ± 0.03 [d]
LSD			*0.071*	*0.40*	*0.15*

4.3.3. *Nutrient concentrations*

Sodium

The Na concentration of the cotton tops, roots and YMLs and the total plant Na concentrations increased significantly with increasing nutrient solution Na:Ca ratio and EC (Table 4-5). Significantly greater percentages of plant Na were translocated to the cotton tops with increasing nutrient solution Na:Ca ratios (P<0.001) but there was no significant effect of nutrient solution EC on Na translocation (P=0.15). Significant interactions were also measured between the effects of nutrient solution Na:Ca ratio and the effects of nutrient solution EC on cotton YML, top and root Na concentrations at harvest and on total plant Na concentrations (P<0.001). There was no significant effect of nutrient solution EC on the cotton Na concentrations at harvest in the 0.2:1 Na:Ca ratio treatments. In contrast, in the 46:1 Na:Ca ratio treatments cotton Na concentrations at harvest increased with increasing nutrient solution EC.

The critical leaf blade concentration at which Na becomes toxic for cotton growth has not yet been established because Na toxicity is difficult to separate from effects of salinity in solution culture experiments and differs according to the cotton varietal capacity to increase vacuolar Na levels (Munns 1993). Generally, a mid-season YML Na concentration of >0.2% indicates that the soil has a surface ESP of >6%, in field situations (Rochester Unpublished). The plants in the treatments of the current experiment with greater than 25 mM Na had YML Na concentrations greater than 0.2%.

Table 4-5 The effect of solution sodium: calcium ratio, electrical conductivity and sodium concentration on the youngest mature leaf, top, root and total plant sodium concentrations of cotton (*Gossypium hirsutum* L.) grown in a nutrient culture system. Values are means of 4 replicates ± standard error. Within columns, means that do not share a common superscript letter are significantly different (*P*=0.05) and ns designates no significant interaction between the effects of nutrient solution sodium to calcium ratio and electrical conductivity.

EC (dS/m)	Na: Ca Ratio	Na (mM)	YML Na (%) @ Squaring	YML Na (%) @ Harvest	Top Na (%)	Root Na (%)	Total Na (%)	Na Translocation to Tops (% of Total)
2.5	**0.2**	**2.2**	0.04 ± 0.00	0.04 ± 0.00 [a]	0.04 ± 0.00 [a]	0.11 ± 0.00 [a]	0.05 ± 0.00 [a]	58.0 ± 2.4
2.5	**4**	**15.0**	0.15 ± 0.01	0.14 ± 0.01 [ab]	0.14 ± 0.01 [ab]	0.40 ± 0.01 [b]	0.19 ± 0.01 [b]	59.5 ± 4.6
2.5	**46**	**20.5**	0.61 ± 0.06	0.46 ± 0.04 [c]	0.46 ± 0.03 [c]	0.45 ± 0.01 [b]	0.46 ± 0.01 [d]	73.8 ± 2.2
4.25	**0.2**	**3.9**	0.05 ± 0.00	0.04 ± 0.00 [a]	0.04 ± 0.00 [a]	0.14 ± 0.02 [a]	0.07 ± 0.01 [a]	49.8 ± 4.2
4.25	**4**	**24.6**	0.18 ± 0.03	0.27 ± 0.07 [b]	0.29 ± 0.07 [b]	0.73 ± 0.02 [c]	0.39 ± 0.04 [cd]	56.6 ± 7.7
4.25	**46**	**36.8**	0.60 ± 0.03	0.70 ± 0.08 [d]	0.71 ± 0.04 [d]	0.93 ± 0.09 [d]	0.75 ± 0.06 [e]	74.2 ± 2.5
6	**0.2**	**5.8**	0.05 ± 0.00	0.03 ± 0.00 [a]	0.05 ± 0.00 [a]	0.17 ± 0.05 [a]	0.08 ± 0.02 [a]	45.0 ± 4.6
6	**4**	**41.1**	0.32 ± 0.05	0.13 ± 0.02 [a]	0.22 ± 0.01 [b]	0.69 ± 0.11 [c]	0.35 ± 0.05 [c]	51.0 ± 9.6
6	**46**	**56.6**	0.80 ± 0.10	0.87 ± 0.06 [e]	0.97 ± 0.07 [e]	1.16 ± 0.07 [e]	1.02 ± 0.05 [f]	69.4 ± 3.5
LSD			*ns*	*0.13*	*0.11*	*0.17*	*0.10*	*ns*

Calcium

As the Na:Ca concentration ratio of the nutrient solution increased there was a significant decrease in the Ca concentration of the cotton tops, roots and YMLs and in the total plant Ca concentrations ($P<0.001$) (Table 4-6). There was no significant effect of nutrient solution EC on the Ca concentrations of the cotton except in the plant tops, where Ca concentrations increased with increasing nutrient solution EC ($P<0.001$).

There was a significant interaction between the effects of nutrient solution Na:Ca and the effects of nutrient solution EC on the cotton YML, top and root Ca concentrations at harvest and on the total plant Ca concentrations ($P<0.05$). There was no significant effect of nutrient solution EC on the cotton YML, root or total plant Ca concentrations at harvest in the 0.2:1 or 4:1 Na:Ca ratio treatments. In contrast, in the 46:1 Na:Ca ratio treatments cotton YML, top and total Ca concentrations at harvest increased with increasing nutrient solution EC. The cotton root Ca concentrations in the 4:1 Na:Ca ratio treatments were not significantly affected by EC. In contrast, in the 0.2:1 Na:Ca ratio treatment cotton root Ca concentrations increased with increasing nutrient solution EC but in the 46:1 Na:Ca ratio treatment cotton root Ca concentrations decreased with increasing nutrient solution EC.

There was a significant effect of nutrient solution Na: Ca ratio and EC on the percentage of plant Ca translocated from the roots to the tops ($P<0.001$) and a significant interaction between the affects of these two nutrient solution factors ($P<0.001$). At the low Ca concentration found in the 2.5 dS/m salinity and 46:1 Na:Ca ratio treatment, the cotton plants translocated a significantly greater percentage of their Ca to the tops than in any other treatment.

The critical leaf blade concentration at which Ca becomes limiting for cotton is 1.9% (Reuter and Robinson 1986). The leaf blade concentrations in all treatments remained above this level and no Ca deficiency symptoms were observed during the experiment.

Table 4-6 The effect of solution electrical conductivity, sodium: calcium ratio and sodium concentration on the youngest mature leaf, top, root and total plant calcium concentrations of cotton (*Gossypium hirsutum* L.) grown in a nutrient culture system. Values are means of 4 replicates ± standard error. Within columns, means that do not share a common superscript letter are significantly different (*P*=0.05) and ns designates no significant interaction between the effects of nutrient solution sodium to calcium ratio and electrical conductivity.

EC (dS/m)	Na:Ca Ratio	Na (mM)	YML Ca (%) @ Squaring	YML Ca (%) @ Harvest	Top Ca (%)	Root Ca (%)	Total Ca (%)	Ca Translocated to Top (% of Total)
2.5	**0.2**	**2.2**	6.38 ± 0.16	6.21 ± 0.16 [a]	5.13 ± 0.14 [a]	1.01 ± 0.04 [b]	4.27 ± 0.15	95.0 ± 0.61 [a]
2.5	**4**	**15.0**	5.06 ± 0.11	5.85 ± 0.24 [ab]	4.43 ± 0.07 [b]	0.68 ± 0.06 [cd]	3.61 ± 0.06	95.9 ± 0.70 [a]
2.5	**46**	**20.5**	2.54 ± 0.07	1.87 ± 0.10 [d]	1.52 ± 0.06 [d]	1.44 ± 0.05 [a]	1.50 ± 0.29	74.2 ± 2.04 [b]
4.25	**0.2**	**3.9**	6.18 ± 0.35	6.38 ± 0.15 [a]	4.88 ± 0.13 [ab]	1.32 ± 0.11 [a]	4.02 ± 0.04	92.0 ± 1.12 [a]
4.25	**4**	**24.6**	5.38 ± 0.64	5.30 ± 0.58 [b]	4.48 ± 0.39 [b]	0.93 ± 0.09 [bc]	3.68 ± 0.07	94.1 ± 1.30 [a]
4.25	**46**	**36.8**	3.53 ± 0.12	2.91 ± 0.23 [c]	2.57 ± 0.13 [c]	0.54 ± 0.15 [d]	2.13 ± 0.11	94.8 ± 1.38 [a]
6	**0.2**	**5.8**	6.69 ± 0.36	6.14 ± 0.30 [a]	5.33 ± 0.13 [a]	1.41 ± 0.11 [a]	4.37 ± 0.04	93.0 ± 0.90 [a]
6	**4**	**41.1**	5.19 ± 0.11	5.13 ± 0.11 [b]	4.94 ± 0.26 [ab]	0.84 ± 0.09 [bc]	3.94 ± 0.26	94.4 ± 1.32 [a]
6	**46**	**56.6**	3.03 ± 0.18	2.88 ± 0.19 [c]	2.76 ± 0.05 [c]	0.43 ± 0.02 [d]	2.14 ± 0.10	94.4 ± 1.03 [a]
LSD			*ns*	*0.77*	*0.52*	*0.27*	*ns*	*3.6*

Potassium

As the Na:Ca concentration ratio of the nutrient solutions increased there was a significant increase in the K concentration of the cotton tops and YMLs and in the total plant K concentrations ($P<0.002$) (Table 4-7). In contrast, the cotton YML, top and total K concentrations decreased with increasing nutrient solution EC ($P<0.001$). Cotton root K concentrations were significantly reduced by increasing nutrient solution Na:Ca ratio ($P=0.02$) and decreased with increasing nutrient solution EC ($P=0.01$). There was a significant interaction between the effects of nutrient solution Na:Ca ratio and the effects of nutrient solution EC on the squaring YML K concentrations, with an increase in YML K concentrations with increase nutrient solution Na:Ca ratio being apparent in the 2.5 and 6 dS/m treatments but not in the 4.25 dS/m treatments.

Increasing nutrient solution Na:Ca ratio and EC had a significant effect on the translocation of K from the cotton roots to shoots ($P<0.001$). There was also a significant interaction between the effects of nutrient solution Na:Ca ratio and the effects of nutrient solution EC ($P<0.001$), with the plants in the 2.5 dS/m salinity and 46:1 Na:Ca ratio treatment, translocating a significantly lower percentage of their K to their tops than in any other treatment.

The critical mid-season leaf blade concentration at which K becomes limiting for cotton growth is 1.5% (Reuter and Robinson 1986). The YML K concentrations in all treatments remained above this level and no K deficiency symptoms were observed during the experiment.

Table 4-7 The effect of solution electrical conductivity, sodium: calcium ratio and sodium concentration on the youngest mature leaf, top, root and total plant potassium concentrations of cotton (*Gossypium hirsutum* L.) grown in a nutrient culture system. Values are means of 4 replicates ± standard error. Within columns, means that do not share a common superscript letter are significantly different (*P*=0.05) and ns designates no significant interaction between the effects of nutrient solution sodium to calcium ratio and electrical conductivity.

EC (dS/m)	Na:Ca Ratio	Na (mM)	YML K (%) @ Squaring	YML K (%) @ Harvest	Top K (%)	Root K (%)	Total K (%)	K Translocation to Tops (% of Total)
2.5	**0.2**	**2.2**	1.87 ± 0.02 [b]	1.72 ± 0.06	3.11 ± 0.13	2.07 ± 0.10	2.90 ± 0.12	95.0 ± 0.61 [a]
2.5	**4**	**15.0**	2.21 ± 0.04 [c]	1.86 ± 0.07	3.16 ± 0.10	1.94 ± 0.12	2.89 ± 0.07	95.9 ± 0.70 [a]
2.5	**46**	**20.5**	2.46 ± 0.07 [d]	2.44 ± 0.09	3.78 ± 0.13	1.88 ± 0.07	3.28 ± 0.14	74.2 ± 2.05 [c]
4.25	**0.2**	**3.9**	2.10 ± 0.05 [c]	1.69 ± 0.05	2.81 ± 0.04	1.96 ± 0.08	2.60 ± 0.02	92.0 ± 1.19 [ab]
4.25	**4**	**24.6**	1.73 ± 0.10 [ab]	1.68 ± 0.03	2.74 ± 0.06	2.52 ± 0.26	2.66 ± 0.06	94.1 ± 1.30 [ab]
4.25	**46**	**36.8**	2.26 ± 0.09 [c]	2.10 ± 0.17	3.38 ± 0.05	1.87 ± 0.15	3.07 ± 0.01	94.8 ± 1.38 [ab]
6	**0.2**	**5.8**	1.66 ± 0.01 [a]	1.58 ± 0.07	2.68 ± 0.10	1.92 ± 0.10	2.49 ± 0.10	92.0 ± 0.90 [b]
6	**4**	**41.1**	1.70 ± 0.04 [ab]	1.64 ± 0.08	2.66 ± 0.19	1.79 ± 0.09	2.45 ± 0.16	94.4 ± 1.32 [ab]
6	**46**	**56.6**	2.26 ± 0.11 [c]	2.08 ± 0.07	2.99 ± 0.22	1.50 ± 0.10	2.58 ± 0.17	94.4 ± 1.03 [ab]
LSD			*0.18*	*ns*	*ns*	*ns*	*ns*	*3.6*

Phosphorus

The effect of the nutrient solution treatments on the P concentrations of cotton plants varied according to both the plant part sampled and the EC of the nutrient solution (Table 4-8). The cotton YML, top and total P concentrations increased with increasing nutrient solution Na:Ca ratio (P<0.05). There was no significant effect of nutrient solution EC on the cotton YML P concentrations (P>0.05) but top (P=0.06) and total plant (P=0.01) P concentrations tended to decrease with increasing nutrient solution EC. There were significant interactions between the effects of nutrient solution Na:Ca ratio and the effects of nutrient solution EC on cotton P concentrations (P<0.05). The increases in YML, top and total plant P concentrations were significant in the 4.25 dS/m treatments but not in the 2.5 or 6 dS/m treatments. Significant variation was apparent between the root P concentrations of the plants in the various EC treatments (P<0.001) and significant interactions were apparent between the effects of nutrient solution Na:Ca ratio and the effects of nutrient solution EC on root P concentrations (P<0.001) but no consistent relationship between either nutrient solution Na:Ca or EC was apparent.

There was no significant relationship between nutrient solution Na:Ca (P=0.82) or EC (P=0.24) on the percentage of plant P translocated from the roots to the tops in the different treatments. The interaction between the effects of nutrient solution Na:Ca ratio and nutrient solution EC on P translocation was significant (P=0.01), with P translocation being decreased with nutrient solution Na:Ca ratio in the 2.5 dS/m treatments and increased with nutrient solution Na:Ca ratio in the 4.25 dS/m treatments but nutrient solution Na:Ca ratio having no significant effect on P translocation in the 6 dS/m treatments

The critical mid-season leaf blade concentration at which P becomes limiting for cotton growth is 0.28% (Reuter and Robinson 1986). The YML P concentrations in all treatments remained well above this level.

Table 4-8 The effect of solution electrical conductivity, sodium: calcium ratio and sodium concentration on the youngest mature leaf, top, root and total plant phosphorus concentrations of cotton (*Gossypium hirsutum* L.) grown in a nutrient culture system. Values are means of 4 replicates ± standard error. Within columns, means that do not share a common superscript letter are significantly different (P=0.05).

EC (dS/m)	Na:Ca Ratio	Na (mM)	YML P (%) @ 3 weeks	YML P (%) @ 5 weeks	Top P (%)	Root P (%)	Total P (%)	P Translocation to Tops (% of Total)
2.5	0.2	2.2	0.85 ± 0.01 ^{a}	0.61 ± 0.02 ^{a}	0.70 ± 0.02 ^{abc}	0.50 ± 0.01 ^{abc}	0.66 ± 0.02 ^{bc}	84.1 ± 1.38 ^{ab}
2.5	4	15.0	0.94 ± 0.02 ^{ab}	0.71 ± 0.03 ^{ab}	0.71 ± 0.03 ^{bc}	0.54 ± 0.02 ^{bcd}	0.67 ± 0.03 ^{bc}	82.7 ± 1.66 ^{ab}
2.5	46	20.5	0.88 ± 0.04 ^{ab}	0.78 ± 0.03 ^{bc}	0.76 ± 0.02 ^{c}	0.54 ± 0.02 ^{bcd}	0.70 ± 0.016 ^{b}	79.4 ± 1.13 ^{bc}
4.25	0.2	3.9	0.90 ± 0.05 ^{ab}	0.71 ± 0.04 ^{ab}	0.66 ± 0.03 ^{ab}	0.57 ± 0.02 ^{d}	0.64 ± 0.03 ^{bc}	78.5 ± 2.26 ^{bc}
4.25	4	24.6	0.81 ± 0.08 ^{a}	0.70 ± 0.10 ^{ab}	0.61 ± 0.07 ^{a}	0.71 ± 0.01 ^{e}	0.63 ± 0.05 ^{bc}	74.9 ± 2.42 ^{c}
4.25	46	36.8	1.16 ± 0.06 ^{c}	0.89 ± 0.03 ^{c}	0.87 ± 0.03 ^{d}	0.56 ± 0.01 ^{cd}	0.81 ± 0.02 ^{a}	85.4 ± 0.56 ^{a}
6	0.2	5.8	0.88 ± 0.04 ^{ab}	0.74 ± 0.06 ^{b}	0.67 ± 0.00 ^{ab}	0.54 ± 0.03 ^{bcd}	0.64 ± 0.01 ^{bc}	79.5 ± 1.52 ^{abc}
6	4	41.1	0.82 ± 0.04 ^{a}	0.72 ± 0.07 ^{ab}	0.67 ± 0.03 ^{ab}	0.46 ± 0.03 ^{a}	0.62 ± 0.03 ^{c}	81.7 ± 3.23 ^{ab}
6	46	56.6	1.01 ± 0.05 ^{b}	0.67 ± 0.05 ^{ab}	0.65 ± 0.03 ^{ab}	0.49 ± 0.02 ^{ab}	0.61 ± 0.02 ^{c}	78.39 ± 2.67 ^{bc}
LSD			*0.14*	*0.12*	*0.09*	*0.06*	*0.08*	*5.92*

Boron

The effect of the nutrient solution treatments on the B concentrations of cotton plants varied according to the plant part sampled (Table 4-9). There was no significant effect of nutrient solution Na:Ca ratio on the squaring YML (P=0.79), root (P=0.56) or total plant (P=0.20) B concentrations. Cotton harvest YML (P=0.002) and top B (P=0.02) concentrations decreased with increasing nutrient solution Na:Ca ratio. Nutrient solution EC had no significant effect on YML or top B concentrations (P>0.05) but root (P=0.02) and total (P=0.02) B concentrations decreased with increasing nutrient solution EC. There was no significant effect of nutrient solution Na:Ca ratio (P=0.11) or EC (P=0.09) on the percentage of the total plant B translocated from the plant roots to tops.

There was a significant interaction between the effects of nutrient solution Na:Ca ratio and the effects of nutrient solution EC on the squaring YML B concentrations of cotton (P=0.001), with the squaring YML B concentrations decreasing with increasing nutrient solution Na:Ca ratio in the 2.5 dS/m treatments but decreasing with increasing nutrient solution Na:Ca ratio in the 6 dS/m treatments. The interaction between the effects of nutrient solution Na:Ca ratio and the effects of nutrient solution EC on B translocation was also significant (P=0.01), with P translocation increasing with nutrient solution Na:Ca ratio in the 4.25 dS/m treatment but decreasing with increasing nutrient solution Na:Ca ratio in the 2.5 and 6 dS/m treatments.

The mid-season YML concentration at which B is considered to be limiting to cotton growth is between 20 and 60 mg/kg (Reuter and Robinson 1986), with cotton responses to B fertilization varying across this range of plant concentrations (Woodruff 2004). The YML B concentrations in all treatments remained above this level.

Table 4-9 The effect of solution electrical conductivity, sodium: calcium ratio and sodium concentration on the youngest mature leaf top, root and total plant boron concentrations of cotton (*Gossypium hirsutum* L.) grown in a nutrient culture system. Values are means of 4 replicates ± standard error. Within columns, means that do not share a common superscript letter are significantly different (*P*=0.05) and ns designates no significant interaction between the effects of nutrient solution sodium to calcium ratio and electrical conductivity.

EC (dS/m)	Na:Ca Ratio	Na (mM)	YML B (mg/kg) @ 3 weeks	YML B (mg/kg) @ 5 weeks	Top B (mg/kg)	Root B (mg/kg)	Total B (mg/kg)	B Translocation to Tops (% of Total)
2.5	**0.2**	**2.2**	109.3 ± 7.7 ^{cd}	164.7 ± 7.9	124.4 ± 3.9	44.8 ± 9.3	108.1 ± 4.8	92.2 ± 2.00 ^{ab}
2.5	**4**	**15.0**	99.0 ± 6.9 ^{d}	152.5 ± 9.6	114.8 ± 15.2	36.3 ± 6.5	83.6 ± 8.0	90.1 ± 2.50 ^{abc}
2.5	**46**	**20.5**	142.0 ± 8.0 ^{a}	121.4 ± 5.8	106.6 ± 20.5	51.5 ± 8.1	80.9 ± 1.2	82.6 ± 3.54 ^{cd}
4.25	**0.2**	**3.9**	123.7 ± 9.4 ^{abcd}	183.2 ± 9.1	104.0 ± 3.7	68.8 ± 12.0	89.8 ± 5.4	81.5 ± 3.82 ^{d}
4.25	**4**	**24.6**	139 .5 ± 4.2 ^{ab}	156.7 ± 9.8	98.5 ± 4.3	62.6 ± 17.8	94.6 ± 6.2	85.8 ± 3.46 ^{bcd}
4.25	**46**	**36.8**	113.6 ± 8.7 ^{bcd}	119.2 ± 6.2	96.6 ± 11.0	36.7 ± 1.3	85.9 ± 3.3	90.5 ± 0.453 ^{abc}
6	**0.2**	**5.8**	129 2 ± 13.3 ^{abc}	180.2 ± 22.1	96.3 ± 6.1	25.5 ± 2.1	92.3 ± 11.0	93.2 ± 0.336 ^{ab}
6	**4**	**41.1**	114.3 ± 12.6 ^{bcd}	174.6 ± 38.2	91.1 ± 0.6	14.9 ± 8.9	82.7 ± 13.1	95.7 ± 2.64 ^{a}
6	**46**	**56.6**	91.5 ± 8.9 ^{d}	135.1 ± 6.0	77.5 ± 3.8	42.2 ± 9.3	67.8 ± 5.2	84.1 ± 3.18 ^{cd}
LSD			*26.4*	*ns*	*ns*	*ns*	*ns*	*7.9*

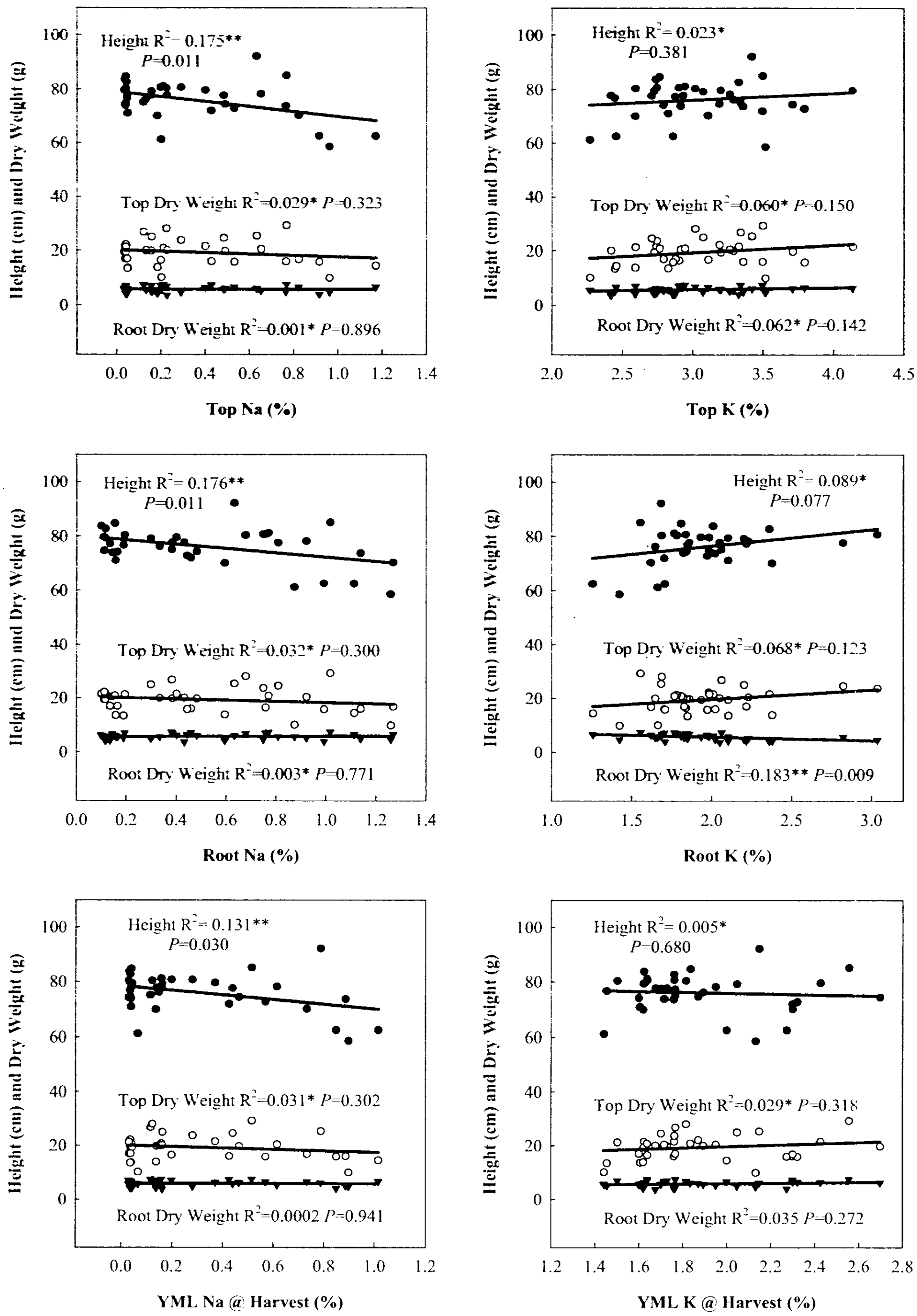
4.3.4. *Correlation between plant growth and nutrient status*

Despite the wide range of plant Na and Ca concentrations measured in this experiment, there were no strong correlations between any plant growth measurements and plant nutrient status (Figure 4-1). Plant height was negatively correlated with top Na concentrations (P=0.01), root Na concentrations (P=0.01) and harvest YML Na concentrations (P=0.03), however these relationships were weak (R^2 values of 0.18, 0.18 and 0.13 respectively). No plant nutrient concentration was correlated with top dry weight but root dry weight was positively correlated with root K concentration (P=0.01). The relationship between root dry weight and root K concentrations was weak (R^2 value of 0.18).

4.4. Discussion

A complex set of interactions between the plant and the chemical and physical condition of the soil contribute to the patterns of nutrient accumulation and plant growth observed in cotton crops grown in sodic soils. This hydroponics experiment allowed the isolation of the effects of soil solution Na from the effects of sodic soil physical condition and elevated pH values on cotton growth and nutrition. Additionally, this experiment allowed the separation of the effects of nutrient solution Na:Ca ratio from the effects of nutrient solution salinity on cotton growth and nutrition.

Figure 4-1 The relationships between the top, root and youngest mature leaf sodium and potassium concentrations of cotton (*Gossypium hirsutum* L.) and plant growth, in a nutrient culture system.



4.4.1. *Plant growth*

Elevated nutrient solution Na concentrations limited cotton height, at a nutrient solution Na concentration greater than 50 mM. Although not significant, there was also a trend towards decreased 4-5th internode length and top dry weight in the 57 mM Na treatment. This Na concentration corresponded to that in the soil solution of a Grey Vertosol with an ESP of between 20 and 25% (Table 4-2). The Vertosols utilised for cotton production in Australia commonly have ESP values ranging between approximately 1 and 25% (Dang *et al.* 2004; Norrish *et al.* 2001; Rochester Unpublished). Thus, the results of this experiment indicate that sodic soil solution chemistry limited early season cotton growth but that this limitation is only apparent at the upper end of the commonly occurring sodicity levels. At moderate sodicity levels, early season cotton growth is largely unaffected by solution Na.

It is difficult to draw robust conclusions regarding the effects of nutrient solution Na on cotton growth from this experiment, due to the early stage of plant growth at harvest necessitated by the practical limitations of the hydroponics system for the growth of mature plants. The comparison of the plant growth results of the current experiment and that outlined in Chapter 5 however, allows more robust conclusions to be reached in both experiments. The experiment described in Chapter 5 outlines the effect of sodicity on the growth and nutrition of cotton in control and polyacrylamide (PAM) amended soils. The inclusion of the PAM treatments in that experiment improved the physical condition of the sodic soils sufficiently to allow the characterisation of the plant responses to soil chemical factors, separately from the plant responses to soil physical factors (Section 3.9). In Chapter 5, increasing soil solution Na resulted in a linear decline in the height and plant dry weight of cotton at maturity, but no effect of soil ESP on plant height was measured until 8 weeks into the growth period (Tables 5-1 and 5-2). This result is comparable with the plant height reductions measured in only the treatment with the highest nutrient solution Na concentration in the current hydroponics experiment, after a 6-week period of growth in the nutrient solution system. The peak period of nutrient demand in cotton is boll filling (Wright 1999) and it is possible that a chemical effect of sodicity on cotton growth would have become apparent in this hydroponics experiment across a wider range of Na concentrations, if it could have been carried through to a later growth stage. It is also feasible however, that excess vegetative growth allowed in the PAM-amended soils of the experiment outlined in Chapter 5 resulted in plant Na concentrations becoming limiting to the vegetative growth of cotton at lower ESP levels than would usually occur

Vegetative growth and plant height reductions were measured in the PAM-amended soils of the experiment outlined in Chapter 5 across sodicity levels ranging from 2 to 24% (Table 5-2). Given the effect of the nutrient solution Na concentrations >50 mM on cotton height and dry matter accumulation at the early plant growth stage at which harvest took place in the current hydroponics experiment, it is likely that this pattern would continue and also translate into smaller cotton plants at the end of the growing season. Seed and lint yield are less significantly affected by sodicity than vegetative growth (Chang and Dregne 1955), so it is unclear whether these vegetative growth reductions would, in turn translate into reduced fruiting and lint yield in the hydroponics system. An indication of the relationship between the chemical characteristics of sodic soils and lint yield at cotton maturity can be gained through an analysis of the results obtained in the PAM-amended soils of the experiment outlined in Chapter 5 (Table 5-2). This experiment determined that sodic soil solution chemistry induced reductions in cotton vegetative growth only translated into lint yield reductions at ESP levels >20%, which again corresponds only to the highest Na treatment of the current experiment. Together the plant growth results of the current experiment and those of the soil based experiment outlined in Chapter 5, suggest that sodic soil solution chemistry, corresponding to that of Grey Vertosols with ESP values greater than approximately 20%, directly limits cotton crop performance.

The cotton roots became significantly thinner in this experiment with increasing nutrient solution Na:Ca, especially at the nutrient solution Na concentration of 57 mM. Kurth *et al.*

(1986) reported a decline in the cross-sectional area of the roots of 6 day old cotton seedlings across a range of Na concentrations from 0 to 250 mM, but only in the presence of 10 mM Ca. These authors reported increases in cotton root cross-sectional area in the presence of only 0.4 mM Ca. Kurth *et al.* (1986) proposed that enhanced root elongation is observed in salt-stressed cotton seedlings because cell elongation is favoured at the expense of radical cell expansion, but that under conditions of low nutrient solution Ca, root cell membrane Ca levels become too low to allow this process to function efficiently. The results presented here suggest that in nutrient solutions similar to those in sodic Grey Vertosols, Na and Ca concentrations may produce thinner cotton roots. The high soil strength typical of sodic soils due to the dispersion of clay particles, may however limit this pattern of root growth under field conditions, as high soil strength causes root cells to enlarge radially rather than axially (Clark *et al.* 2003).

Kurth *et al.* (1986) also reported declining cross-sectional area of individual cortical cells within cotton seedling roots, with increasing nutrient solution NaCl concentrations from 0 to 250 mM, but only in the presence of 10 mM Ca. Increases in cortical cell cross-sectional area were reported by these authors in the presence of only 0.4 mM Ca. No significant consistent relationship between nutrient solution Na concentrations or Na:Ca ratio on cortical cell area was measured in our experiment. A decrease in stele cell area was measured however, indicating that even at the moderate Na concentrations commonly found in the solutions of sodic soils there is an effect of Na on root growth at a cellular level and that this may translate into morphological differences in cotton roots at the whole-plant level.

4.4.2. *Nutrient concentrations*

Cotton produced under sodic field conditions accumulates elevated concentrations of Na and reduced concentrations of K and P in its tissues (Chapter 2). The results of the current experiment demonstrate the patterns of nutrient accumulation occurring in cotton plants produced in solutions mirroring the soil solutions of Grey Vertosols with ESP values up to approximately 25%, without the interference of soil physical factors or extreme soil pH values. Cotton accumulates Na in its shoots and roots with increasing soil solution Na but is also able to maintain the selectivity of its membranes for K and P. The discrepancies between the K and P results of this experiment and the data recorded under field situations suggest the importance of soil physical factors in determining the nutrient accumulation of cotton produced under sodic conditions, with factors such as high soil strength and increasing incidence of waterlogging potentially reducing the ability of cotton to selectively accumulate P and K.

Sodium

The majority of the agriculturally significant varieties of cotton are Na-including plants, which means that one of their central mechanisms of tolerance to sodic conditions is to accumulate significant quantities of Na and sequester this nutrient within plant structures (Lauchli and Stelter 1982; Leidi and Saiz 1997). The increases in both cotton root and shoot Na concentrations and the increasing percentage of Na translocated from the roots to the shoots that occurred with increasing nutrient solution Na suggest that Na is stored throughout the plant but that at high growth medium Na concentrations, greater proportions of plant Na are translocated to cotton shoots for storage.

The Na concentrations of the plants in the low Na treatments of this experiment were similar in magnitude to those of the plants in PAM-amended soils of the non-sodic treatment of the experiment outlined in Chapter 5. The Na concentrations of the plants in the high Na treatments of this experiment were much larger than those of the plants in the PAM-amended soils of the highly sodic treatment. For example, the plants in the treatment with a nutrient solution Na concentration of 3.9 mM had squaring YML Na concentrations of 0.05% while the plants in the treatment with a nutrient solution Na concentration of 36.8 mM had squaring YML Na concentrations of 0.60%. In the PAM-amended soils of the experiment outlined in Chapter 5, the non-sodic and most sodic treatments had soil solution Na concentrations of 3.9

mM and 34.8 mM respectively and this in turn resulted in YML Na concentrations at squaring of 0.04% and 0.09% respectively (Table 5-4). A likely explanation for this discrepancy is that in the nutrient culture system, the Na was instantly available to the plant, increasing the rate of nutrient absorption. Additionally, it is likely that the favourable soil-less environment of the nutrient culture system allowed greater root growth than the soil systems and thus the plants developed greater root surface area for absorption of Na.

Calcium

The significant effect of nutrient solution Na:Ca ratio on the Ca concentrations of the cotton plants has two mechanisms. Firstly, the cotton plants responded to nutrient solution Ca concentrations, with plant Ca falling with decreasing nutrient solution Ca. This response was further exacerbated by decreases in nutrient solution Ca activity, in response to increasing nutrient solution Na, as reported by Cramer *et al.* (1987). At the lowest nutrient solution Ca concentration, the cotton responded by translocating a significantly higher percentage of Ca from the roots to the shoots than in the other treatments. The plant concentrations of Ca in all treatments however, remained above the level at which they become limiting to cotton function.

The Ca concentrations measured in this experiment therefore suggest that in nutrient solution conditions mirroring the soil solution of Grey Vertosols with ESP values ranging from 2-25%, Ca deficiency is unlikely to limit cotton production. This outcome is supported by the results of the field-based experiments outlined in Chapter 2 (Figure 2-6) and by Rochester (Unpublished).

Potassium

The effect of growth medium Na concentrations on the K status of plants is unclear, with some authors reporting decreases in tissue K with the addition of NaCl to the growth media (Ben-Hayyim *et al.* 1987; Kent and Lauchli 1985; Nakamura *et al.* 1990) and others reporting little change or increasing K tissue concentrations with the addition of NaCl to the growth media (Boursier and Lauchli 1990; Kinraide 1999). A likely explanation for these discrepancies is that K efflux is induced from plant root cells through two NaCl related mechanisms and that the extent of K efflux depends upon the growth medium characteristics in each experiment. Firstly salinity causes non-ion specific, osmotically-induced changes in plasmalemma permeability of cotton root cells, that result in K efflux at NaCl levels greater than 100 mM in a one-tenth concentration Hoaglands solution (Cramer *et al.* 1985). Secondly, Na displaces Ca from the membranes of cotton root cells, causing them to leak intercellular K at NaCl concentrations greater than 150 mM in a one-tenth concentration Hoaglands solution. This specific ion effect is only significant however under conditions of low Ca (0.4 mM) (Cramer *et al.* 1985). The reduced top and root K concentrations measured in this experiment with increasing nutrient solution EC correspond with the non-specific K efflux mechanism, despite the fact that the maximum Na concentration utilised was 57 mM. This discrepancy in threshold NaCl concentrations is likely due to the contributions of other nutrient solution components, such as elevated concentrations $CaCl_2$, to the osmotic effect in our experiment, above that which occurs in a one-tenth concentration Hoaglands solution utilised by Cramer *et al.* (1985) . It is unlikely that Na-specific K efflux occurred in this experiment however, given that the total plant K concentrations increased with increasing nutrient solution Na:Ca ratio and that the NaCl concentrations used were well below the 150 mM NaCl threshold outlined by Cramer *et al.* (1985).

The top and YML K concentrations in our experiment increased with increasing nutrient solution Na:Ca ratio. In contrast, the concentrations of K in the plant roots were lower than those in the tops and decreased with nutrient solution Na concentrations and Na:Ca ratio. Similar results were obtained by Reid and Smith (2000), who observed a decline in wheat seedling root K concentrations with increasing solution Na, and a positive correlation between root K concentrations and plant growth. No causal relationship between root K depletion and plant growth was observed by Reid and Smith (2000), and the mechanism behind this pattern of nutrient accumulation was not determined. Kinraide (1999) reported that depletion of K by Na was not a cause of Na toxicity in wheat seedlings. Similarly, no significant relationship between shoot K and cotton growth was observed in our experiment. A correlation was apparent however between decreased root K concentrations and decreased root dry weight and plant height but the causality of the relationship remains unclear. Given the increases in both the cotton top K concentrations and the percentages of plant K translocated to the plant tops with increasing solution Na:Ca, it is likely that discrepancies between root and shoot K concentrations occurred as a result of the stimulation of K translocation from root to shoot, rather than the loss of K from plant roots. The implications of this reduction in root K for cotton performance in sodic soils are unclear however and require further investigation. No reduction in the root K concentrations of the plants in the PAM-amended soils of experiment outlined in Chapter 5 was measured however (Table 5-5), suggesting that a sodic soil solution chemistry induced depletion of root K is not a significant factor limiting the performance of mature cotton plants.

Phosphorus

The P concentrations utilised in this experiment were higher than those commonly measured in the soil solutions of sodic soils and as such, any effects of nutrient solution Na on the P accumulation of cotton need to be interpreted cautiously. The trend towards little change or a slight increase in cotton P concentrations with increasing nutrient solution Na:Ca ratio however suggests that nutrient solution Na does not significantly limit the accumulation of P by cotton. The trend towards slight increases in plant P concentrations with increasing nutrient solution Na:Ca may be attributable to the negative effect that higher solution Ca has on solution phosphate activity (Cramer *et al.* 1986). The P results of this experiment correspond to those in the PAM-amended soils of the experiment outlined in Chapter 5, where no effect or a slightly positive effect of sodicity on cotton P concentrations was measured (Table 5-6). Together the results of these two experiments suggest that P nutritional problems in sodic soils are not due directly to elevated soil solution Na concentrations.

Boron

Although variable, the results of this experiment suggest that there is a trend towards a negative effect of growth medium Na on the B concentrations of cotton. Sodium and boron transport into animal cells has been determined to take place through a number of shared channels (Park *et al.* 2004) and although less advanced, work in plants has suggested that boron pumps are similar in plants and animals (Takano *et al.* 2002). The results of the current experiment suggest that there is the potential for Na to reduce accumulation of B by cotton at the plant membrane, perhaps through a competition for uptake in these shared channels. This effect is unlikely to be important in sodic field conditions however, as B availability is increased by high soil solution Na concentrations (Keren and Gast 1981), frequently resulting in B toxicities rather than deficiencies (Cartwright *et al.* 1986).

4.4.3. *Correlation between plant growth and nutrient status*

Correlation between top, root and YML Na concentrations and plant height were measured in this experiment but these relationships were not very strong (Figure 4-1). No correlations were apparent between plant dry matter accumulation reductions in the most sodic nutrient solution and plant concentrations of either Na or Ca. Similarly, although a correlation was apparent between decreased root K concentrations and decreased root dry weight and plant height, the causality of the relationship remains unclear.

The early stage of plant growth at harvest of this experiment meant that no large effects of nutrient solution treatments on cotton growth were measured. The results of the experiment outlined in Chapter 5 suggested that sodic soil solution chemistry had the greatest potential to limit cotton growth after more than 8 weeks of plant growth, when significant fruit production had commenced (Table 5-1). Correlation between cotton growth and nutrient accumulation were therefore likely to be more meaningful at a later stage of plant growth.

4.5. Summary: the role of sodic soil solutions in determining the nutrient status of cotton in the field

Soil sodicity is related to reductions in both dry matter accumulation and lint yield in cotton crops produced in sodic field situations (Figure 2-6). In this experiment, nutrient solution Na concentrations corresponding to the soil solutions of Grey Vertosols with low to moderate ESP levels had no effect on the growth of cotton, despite significant changes in the Na and Ca status of the plants. At nutrient solution Na corresponding to the soil solutions of Grey Vertosols with ESP levels >20% however, reductions in plant height were measured. Robust conclusions regarding the effects of nutrient solution Na concentrations on cotton growth cannot be drawn from this experiment, due to the early stage of harvest, but the negative effect of elevated nutrient solution Na concentrations on cotton height is supported in mature cotton by the results measured in the PAM-amended soils of the experiment outlined in Chapter 5 (Table 5-2). This reduction in vegetative growth only translated to a negative effect on lint yield in the PAM-amended soils, at ESP values >20%.

The significant relationships that were measured in the current experiment between nutrient solution Na:Ca ratio and plant concentrations of Na illustrate the important role that soil solution chemistry plays in determining the Na status of cotton plants. Soil physical factors are also likely to contribute to the Na status of cotton plants in field situations however, as the poor physical condition and increased incidence of waterlogging events associated with sodic soils (Jayawardane and Chan 1994) has been found to damage root Na exclusion mechanisms due to root anoxia (Drew and Lauchli 1985).

The trend towards higher top and YML K concentrations with increasing nutrient solution Na:Ca ratios suggests that the observed K deficiencies in cotton plants grown in sodic soils are due largely to the poor physical condition of sodic soils reducing root growth and thus nutrient accumulation. This result is supported in mature cotton by the increasing cotton top concentrations of K with increasing soil sodicity, measured in the PAM-amended soils of the experiment outlined in Chapter 5 (Table 5-5). A correlation was apparent in the current experiment between decreased root K concentrations and decreased root dry weight and plant height but further experimentation is required to determine the causal significance of this relationship. No such relationship was measured in the PAM-amended soils of the experiment described in Chapter 5 however, suggesting that depletion of root K may not be important in mature cotton plants exposed to sodic soil solution chemical conditions. Kuchenbuch *et al.* (1986) demonstrated a negative effect of soil strength on root growth and K accumulation. Further experimentation to determine the relative effect of poor soil physical condition on the K concentrations of cotton in sodic soils is outlined in Chapter 5. Another possible explanation for the K deficiencies measured in cotton plants grown in sodic soils is that the poor physical condition of sodic soils increases the incidence and/or severity of waterlogging events and thus reduces the uptake of K. The negative impact of waterlogging on K accumulation has been demonstrated by a number of authors (Drew and Dikumwin 1985; Letey *et al.* 1962; McLeod 2001) who specified the reliance of K uptake on adequate O_2 in the rhizosphere. Further experimentation to determine the impact waterlogging on the K concentrations of cotton in sodic soils is outlined in Chapters 6 and 7.

The trend towards a slightly positive effect of increasing nutrient solution Na:Ca ratio on the P accumulation of the cotton plants suggests that the observed P deficiencies in cotton grown in sodic soils are not due directly to sodic soil solution chemistry. This result is supported in mature cotton by the increasing cotton top concentrations of P with increasing soil sodicity, measured in the PAM-amended soils of the experiment outlined in Chapter 5 (Table 5-6). Cornish *et al.* (1984) demonstrated a negative effect of soil strength on root growth and plant P accumulation and Drew and Dikumwin (1985) demonstrated the negative effect of waterlogging on plant P accumulation. Further experimentation to determine the relative importance of soil strength and waterlogging in determining the P concentrations of cotton in sodic soils is outlined in Chapters 5, 6 and 7.

Chapter 5. The relative effects of the physical and chemical characteristics of sodic soils on the growth and nutrition of cotton (*Gossypium hirsutum* L.)

5.1. Introduction

Approximately 23% of the Australian landmass (NLWRA 2002) and 80% of the irrigated agricultural area in Australia is occupied by sodic soils (Rengasamy and Olsson 1993). Rengasamy (2001) estimated that more than 50% of soils used for high value crops such as cotton are affected by sodicity. Cotton crops produced on sodic soils commonly accumulate reduced concentrations of P and K in their tissues (Rochester Unpublished). Despite the prevalence of sodic soils in cotton production systems, the mechanisms driving these patterns of nutrient accumulation are poorly understood.

Investigations into the mechanisms behind poor crop performance in sodic soils using naturally occurring soils varying in ESP, either in the field or in a glasshouse situation, are confounded. Soil variability between different sites and down the soil profile makes it difficult to separate the effects of sodicity on crop responses from that of other soil properties such as clay mineralogy, soil texture, nutrient status, salinity and organic matter content. In order to isolate the effect of sodicity on plant growth and nutrition, soils of varying ESP were created from one soil, as is outlined in Chapter 3, minimising the risk of other soil properties confounding the experiment. The soil pH and soil solution P concentrations unavoidably increased with ESP; these factors may have affected plant performance in association with soil ESP, hence care is required to interpret the results of this experiment.

Both the adverse physical and chemical characteristics of sodic soils can induce nutrient deficiencies and toxicities in plants (Curtin and Naidu 1998). Sodicity allows for structural deterioration of the soil, reduced hydraulic conductivity and increased susceptibility to surface crusting, hard setting and waterlogging (Levy *et al.* 1998). These factors can limit plant productivity by reducing seedling emergence and root activity and altering nutrient uptake. Sodic soils can also have low redox potential, high soil pH and high soil solution Na concentrations (Curtin and Naidu 1998). These factors can also limit plant productivity and alter nutrient uptake by changing the availability of nutrients to plant roots. In order to better understand the mechanisms behind poor crop performance in sodic soils, there is a need to quantify the relative contributions of physical and chemical limitations of sodic soils to the growth and nutrient accumulation of crop plants. To reduce the physical limitations of sodicity, soils were treated with polyacrylamide (PAM) (CW Pacific Pty Ltd), an anionic linear copolymer of acrylamide and sodium acrylate, commonly used in irrigated agriculture for improving water infiltration and reducing soil erosion and runoff. The results presented in Chapter 3 demonstrated that the addition of PAM to sodic soils is a suitable method for overcoming soil structural deterioration used in pot experiments. Soils amended with PAM maintain their physical condition across a range of ESP values. This allowed the effects of sodic soil chemistry on plant performance to be assessed in the various sodicity treatments in the PAM-amended soils. It was also possible to assess the effects of the combined physical and chemical condition of sodic soils on plant performance through a comparison of plant responses to varying levels of soil sodicity in unamended soils. The small effects of PAM on the physical condition of non-sodic soils and on the availability of P however, means that caution must be employed when attributing differences in plant performance and nutrition between the control and PAM-amended soil directly to soil physical fertility.

This chapter reports a glasshouse experiment using a Grey Vertosol with an extended range of sodicity levels, with and without the addition of PAM. This experiment aimed to assess the relative effects of the chemical and physical characteristics of sodic Grey Vertosols on the growth and nutrition of cotton.

5.2. Methods

5.2.1. *Soil preparation*

The soil was collected from a cotton field at the Australian Cotton Research Institute, Myall Vale, NSW (150°E, 30°S), which had been used for irrigated cotton and wheat cropping for approximately 25 years. The soil was a fertile dark greyish brown cracking clay, classified as a fine, thermic montmorillonitic Typic Haplustert (Soil Survey Staff 2003) or a Grey Vertosol (Isbell 1996). Selected soil properties are presented in Appendix 1.

This soil was treated according to the sodification method outlined in Chapter 3. A bulk 250 kg soil sample of each sodicity treatment was produced, thoroughly mixed and divided into two equal sub-samples. One sub-sample of each sodicity treatment was spread out in a large stainless steel tray and a solution of PAM was applied at a rate of 0.25% (w/w). The soil was allowed to air dry.

The experiment consisted of four ESP treatments (~2.4, 12.7, 19.4 and 24.1%) with three 40 kg replicates of each control and PAM treatment. The soil for each replicate was weighed into pots 75 cm in height and 30 cm in diameter. The base of each pot was sealed with a plastic bag, in order to prevent the leaching of any excess salts from the profile. The large volume of soil was needed to allow the plants to grow to maturity and to express their full lint yield potentials.

5.2.2. *Experimental methods*

This experiment was carried out in a glasshouse situated at the University of New England, Armidale, Australia. The temperature in the glasshouse was maintained within the range of 20 to 35°C. The experiment was undertaken between October and February so that the cotton plants experienced normal day-length and light conditions.

Before planting, fertiliser was incorporated into the top 20 cm of each pot; 200 kg/ha of N as urea, 20 kg/ha of P as $NH_4H_2PO_4$ and 2 kg/ha of Zn as $ZnSO_4$. Initially the soil and pot were weighed and the soil brought to field capacity (~ 42% w/w). Ten seeds of cotton (cv Sicot 289BR, CSD Pty Ltd) were planted into each pot and the pot covered with plastic to prevent excessive evaporation. When the plants reached the two-leaf stage the plastic was removed and the plants thinned to one per pot.

Throughout the experimental period each pot was watered by weight to field capacity when a water content of ~30% (w/w) was reached. One application of Confidor 200SC (*Imidacloprid*) (Bayer Crop Sciences Pty Ltd) was applied to the experiment at the 12 node stage, in order to control cotton aphid (*Aphis gossypii* Glover). Two-spotted mites (*Tetranychus urticae* Koch) were controlled during the experiment with the use of predatory mites (*Phytoseiulus persimilis*) (Beneficial Bugs Co.). The plants were harvested after 18 weeks, when maximum height was reached and the fruit matured.

5.2.3. *Plant measurements*

Plant height, number of nodes, number of fruit and 4-5th shoot internode length were measured monthly during the growth period and at harvest (18 weeks after planting). At plant harvest, plant shoot, root, fruit and lint dry weights and total numbers of fruiting positions were measured. At 8 weeks after planting, early in the fruiting period, the youngest mature leaf (YML) was taken from each plant. At harvest, the plants were removed from the soil and rinsed in deionised water before measurements were taken and the plants separated into YMLs, roots, shoots, fruit and lint. Due to the large volume of soil utilised in the experiment, it was impossible to remove the total root mass of each plant from the soil and so only the main taproot of each plant was harvested.

5.2.4. *Determination of nutrient composition*

The mid-season and harvest YML samples and harvest shoot, root and fruit samples were dried at 80°C and ground to <2 mm. The samples were digested with perchloric acid and hydrogen peroxide, using the sealed chamber method outlined by Anderson and Henderson (1986). The Ca, Na, K, P, B, Cu, Fe, Mn and Zn concentrations of the samples were analysed using inductively coupled plasma atomic emission spectroscopy (ICPAES). An Australasian Soil and Plant Analysis Council (ASPAC) plant sample was included in the analysis, to ensure the accuracy of the results.

5.2.5. *Statistical analysis*

The replicates in this experiment were arranged in a randomised block design. Analyses of variance (ANOVA) were used to test the significance of treatment differences ($P<0.05$), with soil sodicity and PAM amendment as factors, and three replicate plants per treatment. Where significant interactions between the effects of sodicity and the effects of PAM amendment were found, differences between individual treatment combinations were further evaluated by least significant difference (LSD) ($P<0.05$) and these values used to inform the labelling of the tables of results with indicators of significance. T tests, assuming equal variances, were used to determine the significance of harvest date on cotton YML nutrient concentrations ($P<0.05$). Linear and exponential curves were used to describe relationships between data and were fitted using Sigmaplot 7th Edition (SPSS Inc.). Statistical analyses were carried out using the Genstat program (7th Edition, Lawes Agricultural Trust) (Payne 1987).

In this analysis, each individual plant was designated as a replicate, despite the treatment of each of the soils within a given sodicity treatment in one equilibration procedure. The use of individual plants as replicates was a valid approach in this experiment, as the aim of the experiment was to assess the response of cotton plants to sodicity and soil PAM amendment. The most significant within-treatment variation in this system was believed to be derived from genetic variation between individual cotton plants and temperature, moisture and light variation between the different pots, validating the use of individual plants as treatment replicates.

Although repeated sampling analysis is generally used for the statistical analysis of repeated plant measurements, the plant measurements in this experiment were analysed separately at each sampling date. The basis for this decision was that the plant growth of cotton is distinct at different periods during the season (early vegetative growth, squaring, boll-filling, growth cut-out etc). Cotton plant growth was analysed at these distinct points to capture the different effects of sodicity on cotton physiology at the different stages.

5.3. Results

5.3.1. *Plant growth*

Early in the experiment, sodicity did not limit the growth of cotton plants. There was no significant effect of ESP on plant height in either the control or PAM-amended treatments after 4 weeks of growth (Table 5-1). Increasing soil ESP significantly ($P<0.05$) decreased plant height 8 to 16 weeks after planting and at harvest in both the control and PAM-amended treatments (Table 5-1 and 5-2). The addition of PAM to the soil did not have a significant effect on plant height at any time during the experiment ($P>0.05$).

A significant negative effect of increasing sodicity on the 4-5th internode length of the plants was first measured 8 weeks after planting ($P<0.05$) (Table 5-1). This effect continued during the middle of the growth period but there was no significant effect of ESP on the 4-5th internode length in either the control or PAM treatments at 16 weeks after planting or at harvest ($P>0.05$) (Table 5-1 and 5-2). There was a significant interaction between the effects of sodicity and the effects of PAM amendment on the 4-5th internode length of cotton at 12 weeks after planting ($P=0.02$), with a significant effect of ESP measured in the PAM treatments at an ESP of 13% but no significant effect of ESP measured in the control treatments until an ESP of 19%.

No significant effect of sodicity on the number of plant nodes was observed in either the control or PAM treatments at any stage during the growth period or at harvest (Table 5-1). There was also no significant effect of PAM amendment on the number of plant nodes at any time during the experiment (Table 5-1 and 5-2). The addition of PAM to the soil did not have a significant effect on the number of plant nodes at any time during the experiment.

Increasing soil sodicity decreased the dry weight of shoots, roots, fruit and seed cotton, the total number of fruiting positions and total number of fruit at harvest in both the control and PAM treatments ($P<0.05$) (Table 5-2). No significant interactions were apparent between the effects of sodicity and the effects of PAM on the shoot dry weight of cotton ($P=0.61$), with decreases in cotton shoot dry weight being apparent across the range of ESP levels in the control and PAM-amended soils. Significant interactions were however apparent between the effects of sodicity and the effects of PAM amendment on the cotton root dry weight ($P=0.02$), seed cotton dry weight ($P=0.03$), fruit numbers ($P=0.02$) and fruiting position numbers ($P=0.01$). In the control treatments, the most significant negative affects of sodicity on cotton root dry matter accumulation, fruit number, fruiting position number and seed cotton yield occurred at low to moderate sodicity levels. Increases in sodicity above 13% had no additional significant affect on these plant measurements. In contrast, sodicity reduced cotton root dry matter accumulation in the PAM-amended soils across the range of ESP levels. Cotton fruit numbers, fruiting position numbers and seed cotton yield did not respond to increasing sodicity in the PAM treatments until the ESP exceeded 20%. Overall, the total vegetative dry matter accumulation of the plants decreased by an average of 41% as ESP increased from 2 to 24%. The seed cotton yield of the plants decreased by 43% in the control treatments and 38% in the PAM treatments as the ESP increased from 2 to 24%.

Table 5-1 The effect of sodicity and polyacrylamide treatment on the plant nodes, plant height and 4-5th internode length of cotton (*Gossypium hirsutum* L.) during the growth period. Values are means of 3 replicates ± standard error. Within columns values with the same letters do not differ significantly ($P<0.05$) and ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	Plant Nodes (No.)				Plant Height (cm)				Internode Length (cm)			
		4 weeks	8 weeks	12 weeks	16 weeks	4 weeks	8 weeks	12 weeks	16 weeks	4 weeks	8 weeks	12 weeks	16 weeks
Control	2	5.3 ± 0.3	7.7 ± 1.0	14.0 ± 1.5	22.7 ± 1.2	19.9 ± 0.8	59.3 ± 1.1	108.5 ± 2.1	136.2 ± 8.2	3.0 ± 0.2	5.2 + 0.3	6.8 + 0.9 ^{bc}	6.3 ± 0.3
	13	5.3 ± 0.3	7.5 ± 1.0	14.0 ± 0.0	21.3 ± 0.7	18.8 ± 0.7	55.8 ± 1.4	101.0 ± 3.7	125.8 ± 1.0	2.9 ± 0.3	4.9 ± 0.5	6.3 ± 0.3 ^{bcd}	5.8 ± 0.9
	19	5.0 ± 0.6	7.4 ± 0.7	14.0 ± 0.6	21.0 ± 0.0	19.9 ± 0.9	53.3 ± 1.2	94.9 ± 1.6	123.4 ± 2.8	3.0 ± 0.1	4.7 ± 0.5	5.3 + 0.2 ^{c}	6.1 ± 0.9
	24	5.0 ± 0.6	7.8 ± 0.3	14.0 ± 0.6	21.0 ± 0.6	19.2 ± 1.0	54.2 ± 1.6	92.4 ± 3.6	121.5 ± 2.4	2.9 ± 0.3	4.8 ± 0.4	5.2 + 0.3 ^{c}	5.9 ± 0.2
PAM	2	5.3 ± 0.3	8.2 ± 0.3	15.0 ± 0.3	22.0 ± 0.0	19.6 ± 1.1	59.3 ± 1.1	110.3 ± 1.2	138.9 + 8.7	2.9 ± 0.5	5.2 ± 0.2	8.1 + 0.5 ^{a}	6.1 ± 0.5
	13	4.7 ± 0.3	8.2 ± 0.3	14.7 ± 0.9	23.0 ± 0.6	19.8 ± 0.7	56.6 ± 2.8	101.0 ± 7.4	127.4 ± 7.0	2.9 ± 0.2	5.1 ± 0.2	7.0 ± 0.8 ^{b}	6.0 ± 0.8
	19	4.3 ± 0.3	7.8 ± 0.3	14.2 ± 0.6	23.0 ± 1.0	18.7 ± 0.6	55.8 ± 1.4	99.9 ± 4.4	124.4 + 2.41	2.7 ± 0.4	4.7 + 0.3	6.1 + 0.9 ^{cd}	5.8 ± 0.3
	24	4.7 ± 0.3	8.2 ± 0.3	14.6 ± 0.3	22.3 ± 0.3	19.9 ± 1.0	54.2 ± 1.6	95.1 ± 2.5	125.5 ± 5.8	3.1 ± 0.2	4.8 ± 0.2	5.9 ± 0.2 ^{de}	5.7 ± 0.2
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*0.74*	*ns*

Table 5-2 The effect of sodicity and polyacrylamide treatment on the plant height, 4-5th internode length, plant nodes, shoot dry weight, root dry weight, fruit dry weight, seed cotton dry weight, total fruit number and total number of fruiting positions at harvest of cotton (Gossypium hirsutum L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. Within columns values with the same letters do not differ significantly (P<0.05) and ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	Plant Height (cm)	4-5th Internode Length (cm)	Plant Nodes (No.)	Shoot Dry Weight (g)	Root Dry Weight (g)	Fruit Dry Weight (g)	Seed Cotton Dry Weight (g)	Total Fruit (No.)	Total Fruiting Position (No.)
Control	**2**	143.3 ± 8.7	6.3 ± 0.3	22 ± 0.6	134.9 ± 8.9	10.8 ± 0.1 cd	27.2 ± 1.3	78.8 ± 4.4 a	31.0 ± 6.0 a	61.0 ± 7.1 a
	13	132.4 ± 1.1	6.0 ± 0.3	21 ± 0.3	84.2 ± 2.4	8.7 ± 1.1 cde	20.3 ± 0.4	53.8 ± 4.4 bc	17.0 ± 0.6 b	33.0 ± 3.1 bc
	19	129.9 ± 2.9	6.1 ± 0.4	21 ± 0.0	76.5 ± 4.6	8.0 ± 0.7 e	18.3 ± 1.6	41.8 ± 1.3 c	15.3 ± 2.4 c	33.0 ± 1.5 bc
	24	131.4 ± 2.4	6.3 ± 0.2	21 ± 0.3	72.9 ± 4.6	8.0 ± 0.3 e	18.7 ± 1.5	40.5 ± 4.2 c	17.0 ± 1.5 b	30.7 ± 2.9 c
PAM	**2**	151.4 ± 9.1	6.4 ± 0.2	22 ± 0.0	168.0 ± 15.1	14.3 ± 0.4 a	40.5 ± 1.2	83.7 ± 4.5 a	32.3 ± 0.9 a	65.3 ± 4.7 a
	13	141.3 ± 7.3	6.0 ± 0.4	22 ± 0.6	130.1 ± 12.1	13.7 ± 0.8 ab	34.5 ± 3.7	79.0 ± 4.8 a	31.7 ± 2.8 a	60.3 ± 3.0 a
	19	140.5 ± 2.5	5.9 ± 0.2	22 ± 0.6	112.8 ± 3.4	11.2 ± 0.4 bc	34.4 ± 0.6	76.4 ± 5.3 ab	31.0 ± 2.5 a	59.7 ± 4.2 a
	24	126.8 ± 6.1	5.9 ± 0.2	21 ± 0.3	106.0 ± 0.9	8.6 ± 0.5 de	27.9 ± 0.8	51.9 ± 6.2 c	23.3 ± 4.2 b	42.7 ± 4.6 b
LSD		*ns*	*ns*	*ns*	*ns*	*2.55*	*ns*	*17.70*	*7.01*	*9.70*

The addition of PAM significantly increased the shoot, root, fruit and seed cotton dry weight of cotton and increased the total numbers of fruit and fruiting positions ($P<0.05$). The percentage increase in cotton reproductive growth observed following the addition of PAM to the soil was dependent upon the level of soil sodicity. In the non-sodic soil and most highly sodic soil, increases in vegetative growth with the addition of PAM did not translate into an increase in seed cotton yield or an increase in the number of fruit or fruiting positions. The positive effects of PAM amendment on the reproductive growth of cotton were greatest at an ESP of 19%, with the plants in the PAM-amended soils accumulating 82% more seed cotton than those in the control treatments at this sodicity level.

5.3.2. *Nutrient concentrations and accumulation*

Calcium

Soil sodicity and PAM amendment had no effect on the concentrations of Ca in any plant part (Table 5-3). An exception to this pattern occurred in the cotton YMLs, with YML Ca concentrations being significantly negatively affected by PAM amendment at harvest ($P=0.03$). Sodicity had a negative effect on the accumulation of Ca in both the cotton shoots ($P=0.002$) and roots ($P=0.01$) but the amendment of the soil with PAM tended to have a positive affect on shoot ($P=0.01$) and root Ca accumulation ($P=0.02$). There were no significant interactions between the affects of sodicity and the affects of PAM on the Ca concentrations or accumulation of cotton in any plant part ($P>0.05$).

Table 5-3 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root calcium concentrations and the shoot and root calcium accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. Within columns values with the same letters do not differ significantly (P<0.05) and ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM	ESP	Ca Concentrations (%)				Ca Accumulation (g)	
Treatment	**(%)**	**YML @ Squaring**	**YML @ Harvest**	**Shoot**	**Root**	**Shoot**	**Root**
Control	**2**	2.52 ± 0.59	2.68 ± 0.10	2.58 ± 0.19	0.47 ± 0.06	3.50 ± 0.38	0.049 ± 0.07
	13	2.60 ± 0.07	3.01 ± 0.06	3.00 ± 0.14	0.46 ± 0.11	2.52 ± 0.28	0.045 ± 0.08
	19	2.39 ± 0.15	2.88 ± 0.14	2.99 ± 0.82	0.43 ± 0.03	2.00 ± 0.29	0.030 ± 0.05
	24	2.09 ± 0.14	3.28 ± 0.15	1.88 ± 0.20	0.47 ± 0.50	1.37 ± 0.11	0.037 ± 0.10
PAM	**2**	2.38 ± 0.11	2.54 ± 0.20	2.23 ± 0.32	0.52 ± 0.04	3.77 ± 0.58	0.067 ± 0.05
	13	2.64 ± 0.36	2.97 ± 0.39	2.40 ± 0.09	0.48 ± 0.03	3.10 ± 0.20	0.062 ± 0.07
	19	2.59 ± 0.14	2.68 ± 0.10	2.28 ± 0.66	0.41 ± 0.02	2.56 ± 0.44	0.049 ± 0.01
	24	3.15 ± 0.03	2.66 ± 0.17	2.84 ± 0.27	0.43 ± 0.04	3.01 ± 0.15	0.034 ± 0.05
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Sodium

Increasing soil sodicity increased both the Na concentration and accumulation in all plant parts ($P<0.05$) (Table 5-4). The amendment of the soil with PAM did not have a significant effect on the cotton Na concentrations in any plant part but increased the Na accumulation in the shoots ($P<0.001$). The YML concentrations of Na tended to increase between squaring and harvest but this effect was only significant at ESP levels greater than 20% ($P<0.05$).

There were significant interactions between the effects of sodicity and the effects of PAM amendment on the squaring, harvest YML ($P=0.04$) and root ($P=0.04$) Na concentrations and on the accumulation of Na in the roots ($P=0.04$). Harvest YML and root Na concentrations and total root Na accumulation were significantly negatively affected by PAM amendment at the highest sodicity level but not in any of the other soils. Additionally, there was a positive effect of sodicity on root Na accumulation in the control treatments, but not in the PAM-amended soils.

Table 5-4 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root sodium concentrations and the shoot and root sodium accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. Within columns values with the same letters do not differ significantly (*P*<0.05) and ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	Na Concentrations (%)				Na Accumulation (g)	
		YML @ Squaring	YML @ Harvest	Shoot	Root	Shoot	Root
Control	**2**	0.03 ± 0.01	0.04 ± 0.01 a	0.06 ± 0.00	0.10 ± 0.01 a	0.08 ± 0.01	0.01 ± 0.00 a
	13	0.06 ± 0.00	0.07 ± 0.00 ab	0.13 ± 0.00	0.28 ± 0.05 cd	0.10 ± 0.00	0.02 ± 0.00 ab
	19	0.07 ± 0.01	0.08 ± 0.01 abc	0.24 ± 0.02	0.32 ± 0.04 de	0.18 ± 0.03	0.03 ± 0.00 bc
	24	0.11 ± 0.01	0.21 ± 0.01 d	0.31 ± 0.03	0.40 ± 0.04 e	0.23 ± 0.01	0.04 ± 0.01 c
PAM	**3**	0.04 ± 0.00	0.05 ± 0.00 ab	0.08 ± 0.01	0.17 ± 0.02 ab	0.13 ± 0.01	0.02 ± 0.00 b
	13	0.05 ± 0.01	0.08 ± 0.02 abc	0.12 ± 0.01	0.19 ± 0.01 bc	0.15 ± 0.01	0.02 ± 0.00 b
	19	0.07 ± 0.01	0.10 ± 0.01 bc	0.20 ± 0.01	0.27 ± 0.01 cd	0.24 ± 0.02	0.03 ± 0.00 b
	24	0.09 ± 0.01	0.13 ± 0.01 c	0.25 ± 0.01	0.30 ± 0.05 d	0.26 ± 0.01	0.03 ± 0.00 b
LSD		*ns*	*0.06*	*ns*	*0.09*	*ns*	*0.012*

Potassium

Increasing soil sodicity decreased the YML K concentrations at both squaring ($P<0.001$) and harvest ($P=0.01$) (Table 5-5). The interaction between the effects of sodicity and PAM amendment on squaring YML K concentrations was also significant ($P=0.02$), with sodicity tending to decrease concentrations in the control treatments but not in the PAM-amended soils. Cotton YML K concentrations decreased by 35% at squaring between the non-sodic and highly sodic soils of the control treatments. The amendment of the soil with PAM had no overall significant effect on YML K concentrations ($P>0.05$), but at squaring, PAM amendment tended to decrease K concentrations in the non-sodic soil but to increase K concentrations in the most sodic soil.

There was no significant effect of sodicity or PAM on shoot or root K concentrations ($P>0.05$). The interaction between the effects of sodicity and PAM amendment on shoot K concentrations was significant however ($P<0.001$), with sodicity decreasing shoot K concentrations in the control treatments by 14% between the non-sodic and highly sodic soils but increasing concentrations in the PAM-amended soils by 22% between the non-sodic and highly sodic soils. A similar interaction was apparent in the root K concentrations ($P=0.07$), with sodicity decreasing root K concentrations in the control treatments by 51% between the non-sodic and highly sodic soils but increasing concentrations in the PAM amended soils by 5% between the non-sodic and highly sodic soils.

Increasing soil sodicity decreased both the shoot ($P<0.001$) and root ($P=0.003$) K accumulation of cotton. The additiŏn of PAM to the soils increased both the shoot ($P=0.004$) and root ($P=0.02$) K concentrations of cotton, although this effect was more apparent in the shoots than in the roots. There was a significant interaction between the effects of sodicity and the effects of PAM amendment on the cotton shoot K accumulation ($P=0.004$), with PAM amendment increasing shoot K accumulation in all but the non-sodic soil.

Table 5-5 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root potassium concentrations and the shoot and root potassium accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. Within columns values with the same letters do not differ significantly (*P*<0.05) and ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM	ESP	K Concentrations (%)				K Accumulation (g)	
Treatment	(%)	YML @ Squaring	YML @ Harvest	Shoot	Root	Shoot	Root
Control	**2**	1.85 ± 0.04 [a]	2.46 ± 0.02	2.28 ± 0.03 [a]	2.26 ± 0.30	3.09 ± 0.24 [a]	0.24 ± 0.03
	13	1.48 ± 0.13 [b]	1.87 ± 0.05	2.11 ± 0.09 [ab]	1.56 ± 0.33	1.78 ± 0.10 [d]	0.13 ± 0.03
	19	1.42 ± 0.11 [b]	1.74 ± 0.03	2.12 ± 0.01 [ab]	1.76 ± 0.28	1.63 ± 0.11 [de]	0.14 ± 0.02
	24	1.11 ± 0.06 [c]	1.61 ± 0.03	1.95 ± 0.08 [bc]	1.10 ± 0.05	1.42 ± 0.06 [e]	0.10 ± 0.01
PAM	**2**	1.47 ± 0.13 [b]	2.19 ± 0.25	1.87 ± 0.11 [c]	1.76 ± 0.35	3.11 ± 0.11 [a]	0.25 ± 0.06
	13	1.48 ± 0.12 [b]	2.08 ± 0.21	2.10 ± 0.11 [ab]	1.84 ± 0.10	2.71 ± 0.12 [b]	0.25 ± 0.00
	19	1.50 ± 0.05 [b]	1.69 ± 0.35	1.92 ± 0.07 [bc]	1.33 ± 0.14	2.42 ± 0.07 [bc]	0.15 ± 0.02
	24	1.48 ± 0.09 [b]	1.85 ± 0.15	2.29 ± 0.06 [a]	1.84 ± 0.37	2.17 ± 0.06 [c]	0.16 ± 0.03
LSD		0.29	ns	0.39	*ns*	*0.36*	*ns*

Phosphorus

Increasing soil sodicity had no significant effect on the P concentrations of any plant part or on the top or root P accumulation at harvest (P>0.05) (Table 5-6). Increasing soil sodicity tended to increase the P concentrations of the roots (P=0.07). There were no significant interactions between the effects of sodicity and the effects of PAM on the cotton P concentrations or accumulation of any plant part (P>0.05).

The addition of PAM to the soil had no significant effect on the YML P concentrations at squaring, the root P concentrations at harvest or on the accumulation of P in the cotton shoots or roots (P>0.05). In contrast, PAM amendment reduced the YML P concentrations (P=0.04) and the shoot P concentrations (P=0.01), by an average of 0.07% at harvest.

Boron

Increasing soil sodicity had no significant effect on the mid-season YML B concentrations of cotton (P=0.24) but decreased YML B concentrations at harvest (P=0.01) (Table 5-7). Cotton shoot B concentrations and accumulation were negatively affected by soil sodicity (P<0.001). In contrast, cotton root B concentrations increased with increasing soil sodicity (P=0.03) but there was no significant effect of sodicity on cotton root B accumulation (P=0.11). The interaction between the effects of sodicity and the effects of PAM amendment on cotton squaring YML (P=0.06), shoot (P=0.06) and root (P=0.05) B concentrations bordered on being significant, with reductions in squaring YML and shoot concentrations and increases in root concentrations being greater in the control than in the PAM amended soils.

Amendment of the soil with PAM did not significantly affect the concentrations of B in any plant part. The accumulation of B by cotton shoots was however significantly increased by PAM amendment (P=0.01).

Table 5-6 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root phosphorus concentrations and the shoot and root phosphorus accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	P Concentrations (%)				P Accumulation (g)	
		YML @ Squaring	YML @ Harvest	Shoot	Root	Shoot	Root
Control	**2**	0.57 ± 0.02	0.37 ± 0.06	0.23 ± 0.01	0.15 ± 0.18	0.31 ± 0.02	0.02 ± 0.02
	13	0.66 ± 0.05	0.43 ± 0.02	0.27 ± 0.03	0.19 ± 0.16	0.23 ± 0.03	0.02 ± 0.01
	19	0.57 ± 0.06	0.41 ± 0.09	0.34 ± 0.03	0.18 ± 0.01	0.26 ± 0.02	0.01 ± 0.01
	24	0.59 ± 0.02	0.46 ± 0.08	0.29 ± 0.03	0.17 ± 0.00	0.21 ± 0.02	0.02 ± 0.01
PAM	**2**	0.49 ± 0.02	0.32 ± 0.02	0.17 ± 0.01	0.15 ± 0.02	0.28 ± 0.04	0.02 ± 0.01
	13	0.58 ± 0.08	0.38 ± 0.06	0.21 ± 0.04	0.15 ± 0.03	0.27 ± 0.04	0.02 ± 0.01
	19	0.63 ± 0.12	0.35 ± 0.04	0.21 ± 0.02	0.17 ± 0.02	0.23 ± 0.01	0.02 ± 0.01
	24	0.46 ± 0.03	0.32 ± 0.03	0.23 ± 0.02	0.19 ± 0.06	0.24 ± 0.01	0.02 ± 0.01
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Table 5-7 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root boron concentrations and the shoot and root boron accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. Within columns values with the same letters do not differ significantly (*P*<0.05) and ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	B Concentrations (mg/kg)				B Accumulation (mg)	
		YML @ Squaring	YML @ Harvest	Shoot	Root	Shoot	Root
Control	2	79.7 ± 8.31	139.7 ± 7.5	108.9 ± .7	91.5 ± 0.8	14.7 ± 1.1	0.99 ± 0.01
	13	102.6 ± 11.4	169.3 ± 12.7	94.7 ± 8.7	46.9 ± 18.9	7.9 ± 0.6	0.36 ± 0.13
	19	99.1 ± 9.0	128.6 ± 13.4	64.9 ± 2.5	61.2 ± 15.6	4.9 ± 0.1	0.50 ± 0.15
	24	88.6 ± 12.1	119.8 ± 9.4	55.1 ± 2.9	106.3 ± 14.7	4.0 ± 0.4	0.99 ± 0.25
PAM	2	106.5 ± 5.2	147.0 ± 9.4	88.2 ± 8.0	47.4 ± 11.4	14.9 ± 2.2	0.66 ± 0.14
	13	93.9 ± 17.2	152.2 ± 6.2	90.7 ± 10.0	79.9 ± 7.8	11.7 ± 1.0	1.09 ± 0.13
	19	67.7 ± 13.7	128.9 ± 5.1	56.9 ± 11.0	42.3 ± 18.6	6.3 ± 1.1	0.47 ± 0.20
	24	60.0 ± 13.9	109.5 ± 3.6	75.4 ± 3.9	82.0 ± 2.9	8.0 ± 0.4	0.71 ± 0.06
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Manganese

The cotton YML (squaring P=0.04; harvest P=0.01) and shoot (P=0.02) Mn concentrations and shoot Mn accumulation (P<0.001) were reduced with increasing soil sodicity (Table 5-8). The Mn concentrations and accumulation of the cotton roots were not significantly affected by soil sodicity (P>0.05). There was no significant effect of PAM amendment on the cotton Mn concentrations or accumulation in any plant part (P>0.05), although the Mn concentrations of the cotton shoots tended to be lower in the PAM-amended soils than in the control treatments (P=0.05). There were no significant interactions between the effects of sodicity and the effects of PAM on the Mn concentrations or accumulation of cotton in any plant part (P>0.05).

Other micronutrients

Increasing soil sodicity and PAM amendment had no significant effect on the concentrations of Cu in the cotton YMLs or shoots and there were no significant interactions between the effects of sodicity and the effects of PAM on YML or shoot Cu concentrations (P>0.05) (Table 5-9). Root Cu concentrations tended to increase with increasing soil sodicity (P=0.01) but there was no significant effect of PAM amendment (P=0.13). There was however a significant interaction between the effects of sodicity and the effects of PAM on root Cu concentrations (P=0.03), with significantly higher root Cu concentrations measured in the 24% ESP soil of the control treatments and the 12 and 24% ESP soils of the PAM-amended treatments. A reduction in the accumulation of Cu in the cotton shoots was associated with increases in soil sodicity (P=0.03) but there was no significant effect of sodicity on root Cu accumulation (P=0.32). The addition of PAM to the soil tended to increase both shoot (P=0.06) and root (P=0.03) Cu accumulation.

Table 5-8 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root manganese concentrations and the shoot and root manganese accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	Mn Concentrations (mg/kg)				Mn Uptake (mg)	
		YML @ Squaring	YML @ Harvest	Shoot	Root	Shoot	Root
Control	**2**	69.8 ± 7.7	63.0 ± 5.4	53.2 + 3.1	21.2 ± 5.5	7.2 ± 0.9	0.23 ± 0.06
	13	60.6 ± 8.2	63.4 ± 1.4	41.3 + 5.3	10.4 ± 0.5	3.5 + 0.5	0.08 ± 0.00
	19	51.7 ± 3.2	45.4 ± 2.7	41.7 + 0.6	11.0 + 2.2	3.2 + 0.2	0.09 ± 0.02
	24	63.6 ± 12.4	62.0 ± 5.5	33.7 + 1.7	12.4 ± 1.1	2.5 + 0.2	0.11 ± 0.02
PAM	**2**	81.5 ± 8.3	87.9 ± 6.6	46.7 + 3.3	14.1 ± 2.9	7.9 + 1.2	0.20 ± 0.04
	13	61.1 ± 1.2	65.7 ± 13.4	28.5 + 2.6	16.0 ± 3.4	5.0 + 0.4	0.22 ± 0.04
	19	54.9 ± 5.2	58.9 ± 4.6	31.3 + 7.1	14.8 ± 3.0	3.5 ± 1.7	0.17 ± 0.04
	24	52.2 ± 2.7	52.7 ± 4.9	32.8 + 1.0	16.5 ± 2.1	3.5 + 0.1	0.14 + 0.04
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Table 5-9 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root copper concentrations and the top and root copper accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. Within columns values with the same letters do not differ significantly (*P*<0.05) and ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	Cu Concentrations (mg/kg)				Cu Uptake (mg)	
		YML @ Squaring	YML @ Harvest	Shoot	Root	Shoot	Root
Control	**2**	13.8 ± 1.1	9.0 ± 1.1	7.8 ± 0.2	9.6 ± 3.3 [ab]	1.1 ± 0.1	0.10 ± 0.03
	13	13.7 ± 1.9	10.5 ± 0.2	7.3 ± 1.1	9.8 ± 4.0 [ab]	0.6 ± 0.1	0.07 ± 0.04
	19	14.2 ± 1.0	9.3 ± 1.0	10.9 ± 0.3	10.1 ± 2.3 [ab]	0.4 ± 0.01	0.08 ± 0.02
	24	13.5 ± 0.7	8.9 ± 0.2	6.7 ± 0.3	13.5 ± 0.9 [c]	0.5 ± 0.0	0.12 ± 0.01
PAM	**2**	14.1 ± 1.2	8.8 ± 0.5	7.4 ± 1.0	8.0 ± 1.4 [a]	1.3 ± 0.3	0.11 ± 0.02
	13	14.7 ± 0.1	10.0 ± 1.0	6.6 ± 0.2	12.1 ± 2.3 [c]	0.9 ± 0.1	0.17 ± 0.02
	19	15.2 ± 0.7	10.8 ± 0.2	7.1 ± 0.6	8.6 ± 0.3 [ab]	0.8 ± 0.1	0.10 ± 0.00
	24	15.2 ± 0.7	10.6 ± 0.4	8.3 ± 0.4	10.5 ± 0.7 [b]	0.9 ± 0.0	0.09 ± 0.00
LSD		*ns*	*ns*	*ns*	*2.4*	*ns*	*ns*

Table 5-10 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root iron concentrations and the top and root iron accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	Fe Concentrations (mg/kg)				Fe Uptake (mg)	
		YML @ Squaring	YML @ Harvest	Shoot	Root	Shoot	Root
Control	**2**	67.8 ± 9.1	80.2 ± 25.2	43.5 ± 6.7	88.1 ± 33.9	5.9 ± 1.0	1.0 ± 0.4
	13	69.8 ± 5.6	64.0 ± 5.2	30.3 ± 4.2	66.7 ± 7.7	2.6 ± 0.3	0.6 ± 0.1
	19	71.0 ± 4.7	62.3 ± 1.9	38.2 ± 2.6	52.7 ± 6.0	2.9 ± 0.1	0.4 ± 0.1
	24	62.1 ± 5.9	78.6 ± 12.8	35.5 ± 2.1	73.5 ± 12.2	2.6 ± 0.0	0.6 ± 0.1
PAM	**2**	77.4 ± 2.4	85.1 ± 17.8	84.8 ± 55.0	59.4 ± 7.7	14.3 ± 10.9	0.8 ± 0.1
	13	74.9 ± 6.8	88.5 ± 7.4	28.8 ± 2.1	65.4 ± 7.0	3.7 ± 0.1	0.9 ± 0.1
	19	76.9 ± 9.2	75.7 ± 5.2	32.4 ± 3.6	67.1 ± 6.9	3.7 ± 0.3	0.8 ± 0.1
	24	73.4 ± 5.6	61.7 ± 1.1	33.0 ± 2.2	72.4 ± 10.3	3.5 ± 0.2	0.6 ± 0.1
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Table 5-11 The effect of sodicity and polyacrylamide treatment on the youngest mature leaf, shoot and root zinc concentrations and the top and root zinc accumulation of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of 3 replicates ± standard error. ns designates no significant interaction between the effects of sodicity and polyacrylamide.

PAM Treatment	ESP (%)	Zn Concentrations (mg/kg)				Zn Uptake (mg)	
		YML @ Squaring	YML @ Harvest	Shoot	Root	Shoot	Root
Control	**2**	46.3 ± 5.1	33.8 ± 7.3	25.4 ± 0.8	17.5 ± 1.9	3.4 ± 0.2	0.19 ± 0.1
	13	46.4 ± 6.0	37.2 ± 1.6	47.4 ± 3.8	18.3 ± 1.5	4.0 ± 0.2	0.12 ± 0.5
	19	57.1 ± 4.9	39.8 ± 6.3	43.8 ± 1.8	20.0 ± 2.7	3.4 ± 0.1	0.16 ± 0.04
	24	44.4 ± 3.9	38.2 ± 3.3	32.1 ± 4.1	24.8 ± 2.4	2.3 ± 0.3	0.23 ± 0.03
PAM	**2**	44.3 ± 3.9	36.0 ± 5.0	33.9 ± 8.8	18.6 ± 2.6	5.7 ± 2.0	0.26 ± 0.05
	13	55.5 ± 0.9	38.7 ± 2.6	34.4 ± 7.0	22.2 ± 1.8	4.4 ± 0.7	0.28 ± 0.01
	19	57.6 ± 2.7	47.0 ± 5.3	38.6 ± 6.0	21.4 ± 2.3	4.3 ± 0.6	0.24 ± 0.03
	24	59.4 ± 5.2	40.7 ± 5.6	46.4 ± 7.3	25.4 ± 2.7	4.9 ± 0.7	0.22 ± 0.03
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

There was no significant effect of sodicity or PAM amendment on the concentrations of Fe or Zn in any plant part ($P>0.05$) (Table 5-10 and 5-11). There was no significant effect of sodicity on the accumulation of Fe or Zn in the shoots or roots and PAM amendment did not significantly affect Fe accumulation in the shoots or roots ($P>0.05$). The addition of PAM to the soil increased Zn accumulation in the cotton shoots ($P=0.01$) and roots ($P=0.01$). There were no significant interactions between the effects of sodicity and the effects of PAM on the Fe or Zn concentrations or accumulation of cotton in any plant part ($P>0.05$).

5.4. Discussion

5.4.1. *Plant growth*

The cotton plants within the control treatments of this experiment were affected by the physical and chemical characteristics of the sodic soils. Plant growth decreased with increasing ESP in the control treatments, suggesting that sodicity significantly limited vegetative growth and fruit production of cotton. The response of cotton to sodicity under field conditions will vary according to soil characteristics and climatic and management factors. Therefore, although the cotton growth response to sodicity measured in this experiment can be used as a guide to determine how a cotton crop will behave under sodic field conditions, the critical ESP values obtained in this experiment should not be applied directly to all field situations. For example, in the field experiment outlined in Chapter 2, a 36% reduction in seed cotton dry weight was associated with an increase in soil sodicity from 1 to 7% and a further 6% reduction in seed cotton dry weight was associated with an increase in soil sodicity from 7 to 27% (Table 2-2). In the control treatment of the current experiment a 32% reduction in seed cotton dry weight was associated with an increase in soil sodicity from 2 to 13% and a further 17% reduction in seed cotton dry weight was associated with an increase in soil sodicity from 13 to 24%. In agreement with the current experiment, the results of the experiment described in Chapter 2 highlight the potential for low to moderate soil sodicity levels to reduce cotton performance. The cotton in the field experiment however, exhibited lower yield reductions in moderate to highly sodic soils that the cotton in the current experiment.

Grey Vertosols can limit plant growth, even in non-sodic conditions as they have a tendency towards swelling when wet and shrinking and cracking when dry (Isbell 1996). An improvement in these characteristics can account for the positive vegetative cotton growth response to PAM, even in the non-sodic soil. Without the physical constraints placed upon plant growth by a Grey Vertosol, the cotton plants in the non-sodic PAM treatment grew more vigorously than the plants in the control treatment, however this did not translate into increased fruit or lint production. The increased plant growth in the PAM-amended soils indicates that the decreases in soil solution P (Table 3-6) as a result of PAM amendment did not significantly limit plant growth. Excessive vegetative growth of cotton has been observed in the field under conditions of high nitrogen and water application and has also been found to have no effect on fruit production and lint yield (Yeates *et al.* 2002). Strong vegetative growth was promoted in this experiment by the continually favourable conditions of the glasshouse environment. The calculated maximum potential lint yield for cotton is 4300 kg/ha (Baker and Hesketh 1969) and the maximum cotton lint yield obtained in an Australian field situation is approximately 3400 kg/Ha (Constable and Bange 2006), with the discrepancy between these figures being attributed to the suboptimal conditions of temperature, light, aeration and nutrition that occur in soil systems (Constable and Bange 2006). The highest yield obtained in this experiment was 3375 kg/ha, which is comparable to the maximum lint yield figure for field grown cotton. This result supports the proposal that the increased dry matter accumulation in the PAM treatments, above the level observed in the non-sodic control treatment, consists of excess vegetative growth and that the lint yield of the non-sodic PAM amended soils was not limited by the experimental conditions.

The inclusion of the PAM treatments in this experiment improved the physical condition of the sodic soils sufficiently to allow the characterisation of the plant responses to soil chemical factors, separately from the plant responses to soil physical factors (Tables 3-8 and 3-9) through a comparison of the plant growth in the varying sodicity treatments of the PAM amended soils. The adverse chemical conditions that plants have been reported to respond to in sodic soil solutions include increasing concentrations of Na and changes in solution pH and redox potential reducing micronutrient availability (Curtin and Naidu 1998). The gradual decline in dry matter accumulation in the PAM treatments with increasing soil sodicity indicates that soil chemical factors placed limitations on the vegetative growth of cotton even at low ESP values. The excessive vegetative growth in the non-sodic PAM treatments however suggests that soil solution Na effects on cotton dry matter accumulation at low ESP levels would not significantly limit cotton production under normal field growing conditions. There was no fruit number, total fruiting position number or lint yield response to sodicity in the PAM treatments, except at the highest sodicity level, which indicates that soil chemical factors limit plant vegetative growth before they limit the production of fruit and lint.

The consistent physical condition of the PAM-amended soils across the range of sodicity treatments (Tables 3-8 and 3-9) means that the relative sizes of the plant growth responses to PAM amendment at the different sodicity levels can be used to determine the extent that soil physical characteristics limit plant growth at a given ESP. Increased vegetative growth of cotton plants with the addition of PAM across the range of sodicity treatments indicates that physical factors were dominant in limiting cotton vegetative growth in this soil at ESP values up to 24%. There was no significant increase in lint yield with the addition of PAM in the non-sodic soil, which indicates that the physical condition of the non-sodic soil was not limiting to cotton lint yield. The increases in lint yield occurring in the plants with the addition of PAM at low to moderate ESP values (13 to 19%) indicate that the physical condition of the soil is the dominant limiting factor affecting lint accumulation at these sodicity levels. There was no significant effect of PAM amendment on the lint yield of cotton at an ESP of 24% however, which demonstrates that at this ESP, chemical factors become equally as limiting as physical factors to cotton reproductive growth.

The magnitudes of the adverse chemical and physical effects of sodic soils on cotton growth are determined by the properties of the individual soil. The concentrations of Na in the soil solution will vary with clay content and mineralogy, due to variations in soil: solution cation equilibriums in different soil types (Kopittke *et al.* 2005; Levy and Hillel 1968). The pH and micronutrient availability of sodic soils will vary according to soil factors such as carbonate content and clay mineralogy (Cruz-Romero and Coleman 1975; Curtin and Naidu 1998). Variations in these factors will not change the nature of the response of cotton to the soil solution composition of different sodic soils but may alter its magnitude at a given ESP value. The physical condition of a soil in response to sodicity varies depending on soil salinity, organic matter, clay mineralogy and texture. In the Vertosol soils that are commonly used for irrigated cotton production in Australia, the dominant factors in determining the physical condition of a soil at a given ESP are clay mineralogy and EC. Specifically, Vertosols with larger proportions of 2:1 clay minerals are more dispersive at a given level of sodicity than those with smaller 2:1 clay mineral contents and Vertosols of varying clay mineralogy are all less dispersive under conditions of higher EC (Speirs 2005). Thus, variation in these factors between different soils will affect the physical condition of a soil at a given ESP and thus affect both the nature and magnitude of the plant growth response to sodicity.

A chemical effect of sodicity on cotton dry matter accumulation at sodicity levels less than 20% was not expected in this experiment, given the results obtained in the previously conducted hydroponics experiment (Chapter 4) which indicated a chemical effect of sodicity on plant height and dry matter accumulation only at soil solution Na levels corresponding to a soil ESP of >20% (Table 4-3). A likely explanation for this difference is that the moderate Na concentrations did not have an effect on plant growth in the hydroponics system due to the early stage of plant growth at which this experiment was harvested. No growth response to sodicity was measured in this pot experiment until 8 weeks into the experimental period. The peak period of nutrient demand in cotton is boll production (Wright 1999) and it is possible that a greater chemical impact of sodicity on cotton growth would have become apparent in the hydroponics experiment if it could have been carried through to a later growth stage. It is also feasible however, that excess vegetative growth observed in the PAM-amended soils of this experiment resulted in plant Na concentrations becoming limiting to the vegetative growth of cotton at lower ESP levels than would usually occur.

5.4.2. *Nutrient concentrations and accumulation*

Calcium

The YML Ca concentration at which cotton is considered to be suffering from Ca deficiency during the growing season is approximately 1.9% (Reuter and Robinson 1986). All of the plants in this experiment exhibited YML Ca concentrations above this level during the experiment and as such Ca deficiency was not likely to have been limited plant growth in either the control or PAM treatments.

Cation uptake in plants is strongly selective for Ca over Na and thus Ca deficiency occurs only when the ratio of Ca: total cations in the soil solution falls below a critical level (Naidu *et al.* 1995). As there was no effect of ESP on Ca concentration or uptake in the PAM treatments of this experiment, there was enough Ca in the soil solution to allow the plant to take up sufficient Ca, despite the presence of high concentrations of Na. Carter and Webster (1990) suggested that a Ca: total-cation-concentration ratio of less than 0.15 in saturated paste extract, indicates where Ca deficiency may limit plant growth. Soil solution analysis of the soils used in this experiment indicated that the concentration of Ca in the soil solution at an ESP of 25% was 2.15 mM and that the Ca: total cation ratio was 0.06 (Table 3-5). Interestingly, despite the low Ca: total cation ratio of this soil solution, the Ca concentration was sufficient to prevent Ca deficiency, perhaps because plant growth was limited by factors other than plant Ca concentration.

Even in the control treatments, where soil physical conditions were not amended, the cotton Ca concentrations were not affected by soil sodicity. The effect of increasing soil ESP reducing Ca uptake but not Ca concentrations in the control treatments indicates that the reduced plant growth in the more sodic soil, limited the plants capacity to accumulate Ca.

Sodium

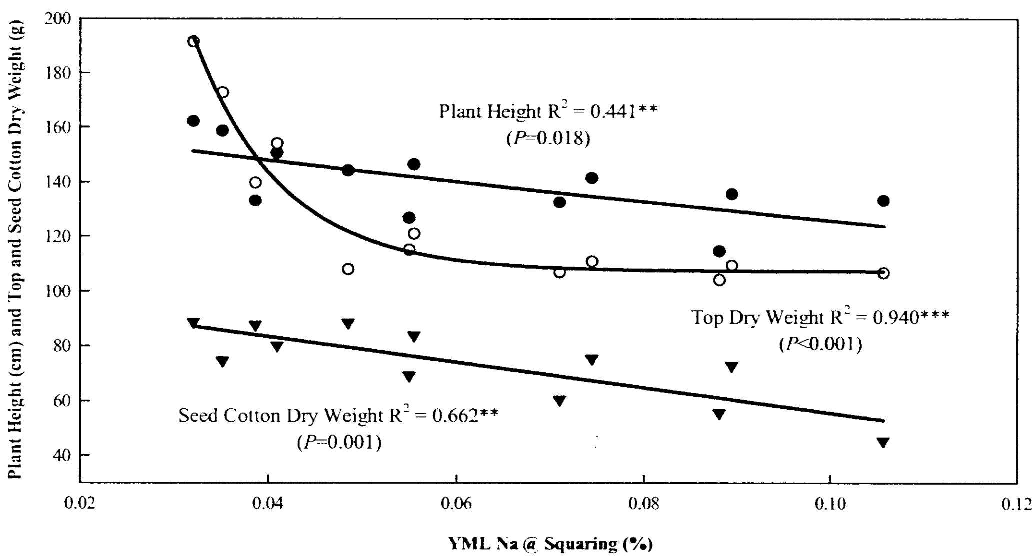
The majority of the agriculturally significant varieties of cotton are Na-including plants, which means that one of their central mechanisms of tolerance to sodic conditions is to accumulate significant quantities of Na and sequester this nutrient within plant structures (Lauchli and Stelter 1982; Leidi and Saiz 1997). Similarly, the concentrations of Na present in all of the plant tissues sampled increased significantly with increasing soil ESP in the current experiment.

Although there was no significant effect of PAM amendment on the cotton Na concentrations in this experiment, in the most sodic treatments amendment of the soil with PAM tended to reduce cotton YML and roots Na concentrations ay harvest (Table 5-4). This result indicates that soil physical condition played a role in determining plant Na accumulation. Sodium concentrations and uptake in cotton plants are increased under conditions of waterlogging (McLeod 2001). This is likely due to the breakdown of Na exclusion mechanisms in the plant roots as anaerobic conditions interfere with energy dependent ion transport processes (Drew and Dikumwin 1985; Drew and Lauchli 1985). Although this experiment was watered only to field capacity, the poor hydraulic conductivity of the soils in the most sodic control treatment could have resulted in uneven wetting and periods of waterlogging for roots in different parts of the pots. The occurrence of waterlogging in the more sodic soils of the control treatments could thus be responsible for the higher Na concentrations in these plants. The physical condition of the soil was nonetheless much less important in determining the Na accumulation of cotton than the chemical condition of the soil, as was indicated by the difference in the Na concentrations of the highest and lowest sodicity treatments in the PAM-amended soils (Table 5-4).

The increase in YML Na concentrations in the most sodic control and PAM treatments between mid-season and harvest can be explained by the plants greater requirements for water and nutrients experienced throughout the boll-filling period when the plants experienced high rates of evapotranspiration and rapid cycles of irrigation and drying. More frequent irrigations resulted in the more frequent waterlogging events, especially at the upper sodicity levels of the control treatments, which could have significantly increased Na uptake as observed in the control treatment at sodicity levels greater than 20%.

The YML Na concentration at which sodicity becomes chemically limiting to cotton production has not been established, due to the difficulty in separating high levels of soil solution Na from other factors, including poor soil physical condition and salinity. The reduced lint yield in the PAM treatment at an ESP of 24% however, indicated that mid-season YML Na concentrations greater than 0.08% could significantly limit cotton crop performance, if not confounded by poor soil physical condition. The mid-season YML concentrations of cotton in the PAM-amended soil were negative correlated with plant height (P=0.02), top dry weight (P<0.001) and seed cotton yield (P<0.001) (Figure 5-1). Similar correlations were apparent when the results of the control and PAM-amended soils were combined (Figure 5-2). These correlations between plant Na concentrations provided no clear causal relationship between cotton Na accumulation and growth, indicating that the accumulation of high concentrations of Na in the plant may have contributed to the reduced growth of cotton that occurred with high soil sodicity but that it was not the only influential factor responsible.

Figure 5-1 The relationship between the mid-season youngest mature leaf sodium of cotton (Gossypium hirsutum L.) produced on a Grey Vertosol amended with polyacrylamide and plant height, top dry weight and seed cotton yield.



Potassium

The effect of sodicity on plant K nutrition has been attributed to both chemical and physical soil properties including limitations to root growth, soil exchange equilibrium shifts and leakage of K from plant roots, due to the displacement of root Ca by Na (Cramer *et al.* 1985).

As with Ca, the cation uptake process in plants is strongly selective for K over Na. As there was no effect of soil sodicity in the PAM treatments on the YML or root K concentrations and the shoot K concentrations tended to increase with increasing soil sodicity, there was no negative chemical effect of sodicity on the K nutrition of cotton, under the optimum range of moisture conditions maintained throughout this experiment. Thus, despite the soil exchange equilibrium shifts that result in extreme Na:K ratios in the soil solutions of sodic soils and despite the physiochemical similarities between K and Na ions, cotton roots were able to access K efficiently even in highly sodic soil. Increasing soil sodicity had a negative effect on the accumulation of K in the shoots of the PAM treatments. Given the K concentration results however, it is likely that reductions in plant growth limited K uptake in these treatments, rather than K concentration limiting plant growth.

The tendency for the K concentrations of cotton shoots in the PAM treatments to increase with increasing soil sodicity can most likely be explained by the reduction in plant dry weight in these treatments. Increased shoots K concentrations were also measured in the hydroponically grown cotton described in Chapter 4 (Table 4-7), but without the same reductions in plant dry weights. In the hydroponic cotton, the increased shoot concentrations of K with increased nutrient solution Na were accompanied by declines in root K concentrations and increased translocation of K from roots to shoots. Increased translocation of K from the cotton roots to shoots with increasing soil sodicity, did not occur in the current experiment however, as no reduction in root K concentrations was observed with increasing soil sodicity. Sodium and potassium are accumulated through some of the same channels in root cells and Na-coupled K uptake is believed to play a role in K acquisition (Box and Schachtman 2000; Rubio *et al.* 1995). Sodium stimulates the transport of K in HKT1 channels in wheat roots (*Triticum aestivum* L.) (Schachtman and Schroeder 1994) and HKT1-like channels in river red gum roots (*Eucalyptus camaldulensis* L.). The physiological function of HKT1 has not yet been determined but it does not appear to be involved in ion acquisition, because Na has not been determined to significantly stimulate growth or K uptake in longer-term experiments with wheat (Box and Schachtman 2000). Thus, although it is possible that increased soil Na concentrations stimulated K uptake in this experiment, this would be contrary to the results obtained by previous authors.

The decrease in K concentrations that occurred with increasing soil sodicity in the control treatments is a significant contrast to the results obtained in the PAM treatments. The negative effect of sodicity on K concentrations in the control treatments indicates that despite the fact that soil solution chemistry had no negative effect on K concentrations in the PAM-amended treatments, the plants in the control treatments were unable to maintain their K nutritional status. This result establishes that soil physical factors, such as limitations to root growth, are primarily responsible for K nutritional problems in cotton crops growing in sodic soils. The decrease in K concentrations in all of the plant parts with increasing soil ESP in the control treatments indicates that K uptake may limit plant growth rather than plant growth limiting K accumulation.

The plants in the control treatments accumulated less K than those in the PAM treatments and this discrepancy was amplified with increasing soil sodicity. The only difference between the K concentrations of the control and PAM treatments occurred in the most sodic treatment however, with the shoot K concentrations being positively affected by PAM application. These results suggest that the significant increases in growth with the addition of PAM across the range of sodicity treatments resulted in a dilution of the K in the plant tissues and limited their ability to accumulate luxury concentrations of K.

The mid-season YML K concentration at which cotton is considered to be suffering from K deficiency is 1.5% (Reuter and Robinson 1986). The concentrations measured in the PAM treatments did not fall significantly below this in any soil sodicity level, suggesting that K nutrition did not limit plant growth in these treatments. The concentrations measured in the control treatments tended to fall below this level at ESP values greater than 19%, suggesting that K nutrition was marginal in these plants. This data supports the conclusion that K nutritional problems that occur in cotton production systems based on sodic soils are due to soil physical constraints rather than chemical factors. No significant correlations were apparent in this experiment however, between YML K concentrations and cotton performance (Figure 5-2), which suggests that although K deficiency may contribute to the declining yield of cotton in sodic soils, in this experiment, factors other than plant K status were more important.

Like Na, the uptake of K by plants can be influenced by soil moisture conditions. Potassium uptake by cotton has been found to decrease both during and after a waterlogging event (Hocking *et al.* 1987; McLeod 2001) due to the root damage and the decreases in root growth that occur in the anaerobic environment of a waterlogged soil (Wiengweera and Greenway 2004). Thus, under the furrow irrigation systems commonly utilised in field situations, the impact of sodicity on soil physical condition could further reduce K accumulation by cotton, due to increases in the frequency and severity of waterlogging events. Further experiments were carried out to address this issue in Chapters 6 and 7.

Phosphorus

The P concentrations of the soil solutions in this experiment rose significantly with increasing soil sodicity (Table 3-5). This result is consistent with those observed by previous authors, who found that P availability tends to increase in sodic soils due to the dissolution of Ca-P compounds and the release of sorbed P with increasing clay surface negative potential (Curtin *et al.* 1992a; Gupta *et al.* 1990). Hence, sodic soil chemistry suggests better P nutrition of cotton through greater availability of soil P. The PAM treatments of this experiment support this proposal, with no effect of sodicity on the YML or shoot P concentrations and the P concentrations of the roots tending to increase with increasing soil sodicity. Additionally, there was no effect of sodicity on the accumulation of P in the shoots or roots of the PAM treatments at harvest. Hence, the P nutritional problems in cotton crops produced under sodic conditions are not due directly to elevated soil solution Na concentrations.

Despite the increase in P availability in the soil solutions of sodic soils, P deficiency is commonly reported in crop plants produced on sodic soils (Naidu and Rengasamy 1993; Rochester Unpublished). It has been hypothesized that these patterns of nutrient accumulation are due to soil physical factors causing reductions in root growth. The P concentrations results obtained in this experiment however do not support this theory, with no significant effects of soil sodicity on the plant P concentrations in the control treatments. It is possible that soil physical factors limited the ability of the plant to access P in the control treatments in the more sodic soils but that increases in P availability mitigated this potential limitation to P nutrition. Significant responses to P fertiliser have been obtained in cotton crops produced on the Grey Vertosols of northern NSW at soil Colwell P concentrations of between 6 and 8.5 mg/kg (Dorahy *et al.* 2002). The Colwell P concentration of the soil used in this experiment was 42 mg/kg (Appendix 1), which indicates that the P fertility was more than adequate. The high P fertility of this soil may have prevented differences in P nutrition with increasing soil sodicity being observed. The accumulation of P in the plant shoots decreased in the control treatments with increasing soil sodicity, but given that soil ESP had no effect on plant P concentrations, it is likely that plant growth was limiting P uptake rather than P concentrations limiting plant growth.

The lack of furrow irrigation and thus extended waterlogging periods in this experiment is another possible explanation for the discrepancy between the P results in this experiment and those observed under field situations. Despite an increase in P availability in waterlogged soils (Ponnamperuma 1972), a decrease in P uptake by cotton has been found both during and after a waterlogging event (Hocking *et al.* 1987; McLeod 2001). This is due to the reduction in root growth and root damage that can occur in the anaerobic conditions of waterlogged soils. An increase in the frequency and or severity of waterlogging events in sodic soils is a possible explanation for the observed P nutritional problems occurring in field situations and this question is addressed in Chapters 6 and 7.

Both the control and PAM treatments had squaring YML P concentrations of approximately 0.5-0.6% across the range of sodicity treatments. Phosphorus is not considered to be limiting to cotton growth at mid-season YML concentrations of greater than 0.28%, indicating that all plants in this experiment were able to accumulate sufficient P, due to the high P fertility of this soil.

The soil solution analysis carried outlined in the PAM application section of Chapter 3 determined that the application of PAM to a soil slightly reduced the availability of P in the soil solution (Table 3-11). A possible consequence of this change in availability was observed in the current experiment, with the control treatments having higher YML and shoot P concentrations at harvest, than the PAM treatments. Phosphorus nutrition did not limit plant growth in the PAM treatments of this experiment however, with the plant in the PAM amended soils producing greater vegetative and reproductive growth than those in the control soils, despite the lower soil solution P status.

Boron

The B results obtained in this experiment are difficult to explain through accepted sodic soil chemistry. Soil solution B concentrations are determined by adsorption and precipitation reactions and these are controlled by pH, exchangeable cations, ionic strength and soil water content (Curtin and Naidu 1998). Increasing pH enhances adsorption of B onto clay minerals due to changes in soil solution B speciation (Hingston 1964). The adsorption of B onto clay minerals is reduced by soil solution Na and increased by soil solution Ca, at pH values greater than 8 (Keren and Gast 1981), which may lead to B toxicity in some sodic systems (Cartwright *et al.* 1986). The significant reduction in the concentrations of B observed in the cotton shoots of both the control and PAM treatments conflicts with the accepted chemistry of sodic soil systems but cotton root B concentrations increased with soil sodicity. A negative effect of solution Na on cotton B concentration was also observed in hydroponics experiment described in Chapter 4, despite the maintenance of constant B levels in all of the treatment solutions. Sodium and boron transport into animal cells has been determined to take place through a number of shared channels (Park *et al.* 2004) and although less advanced, work in plants has suggested that boron pumps are similar in plants and animals and shared B and Na pumps have been implicated in the transport of B from plant roots into the xylem (Takano *et al.* 2002). It is therefore possible, given the results of the current experiment, that Na reduced the transport of B from the roots to shoots through a competition for uptake in these shared channels, decreasing shoot B concentrations and increasing root B concentrations with increasing soil sodicity.

The addition of PAM to the soil did not significantly affect the B concentrations of cotton across the variety of plant parts sampled. The B accumulated in the shoots was increased with the addition of PAM, due to increases in dry matter accumulation. The mid-season YML concentration at which B is considered to be limiting to cotton growth is between 20 and 60 mg/kg (Reuter and Robinson 1986), with cotton responses to B fertilization varying across this range of plant concentrations (Woodruff 2004). All plants in the current experiment had adequate YML B concentrations at squaring. The plants in the most sodic PAM treatments were bordering on being B deficient but no correlations were apparent between YML B concentrations and cotton performance (Figure 5-3) and no symptoms of B deficiency were observed.

Manganese

Manganese deficiency has been widely reported in crops produced on sodic soils (Northcote 1988; Williams and Raupach 1983). The availability of Mn in sodic soils is largely controlled by soil pH, with Mn deficiency being associated with alkaline soils because of the formation of insoluble oxides. Above pH 7, Mn availability has been found to decrease logarithmically, reaching a minimum value at pH 9 (Lindsay 1979). The tendency of sodic soils to become waterlogged has the potential to increase the availability of Mn to the plant however, with Mn^{4+} being reduced to Mn^{2+} as soil redox potential falls (Ponnamperuma 1972). The significant reduction in cotton Mn concentrations that occurred in the PAM treatments of the current experiment with increasing soil sodicity suggest that increasing soil pH values were responsible for reductions in the availability of this nutrient to the plants.

The YML concentration at which Mn limits cotton performance is between 30 and 50 mg/kg (Reuter and Robinson 1986). All of the plants in the current experiment had sufficient YML

Mn concentrations at squaring. The Mn concentrations in the YMLs of the more sodic PAM treatments and of the 19% ESP control treatments were marginal however and hence could be bordering on limiting growth in these plants. Correlations were apparent between cotton mid-season YML Mn concentrations and the measured parameters of plant height and shoot dry weight (P<0.05) (Figure 5-3) but no direct causal relationship was established. Together these results suggest that Mn deficiency may have contributed to the decline in performance of the plants in the PAM treatments with increasing soil sodicity, but given that the YML Mn concentrations were only bordering on deficiency, was not likely to have been the key causal factor.

Other micronutrients

Zinc, copper and iron deficiencies have been frequently reported in sodic soils, due to increases in pH and the occurrence of more frequent and more severe waterlogging events reducing the availability of these nutrients (Curtin and Naidu 1998). There was no significant negative effect of sodicity on the concentrations of Cu, Fe or Zn in any plant part or treatment, which suggests that the chemical availability of these nutrients or physical condition of the soil did not reduce the ability of the plants to access these nutrients. The tendency for cotton root Cu concentrations to increase with increasing soil sodicity is probably due to dry matter reductions, rather than any direct effect on nutrient availability. Additionally, there was no significant effect of PAM amendment on the cotton Cu, Fe or Zn concentrations, which suggests that the physical condition of the soil did not reduce the ability of the plants to access these nutrients. The reduced accumulation Cu in the shoots of the control treatments with increasing soil sodicity is due to reductions in plant growth, resulting from other experimental factors.

The mid-season YML concentrations at which Cu, Fe and Zn become limiting to cotton growth are 5 mg/kg, 50 mg/kg and 20 mg/kg respectively (Reuter and Robinson 1986). All of the plants in this experiment maintained Cu, Fe and Zn concentrations above these critical levels. Hence these nutrients did not significantly limit plant growth in this sodic Grey Vertosol.

5.5. Summary – the relationship between cotton nutrition and performance in sodic soils

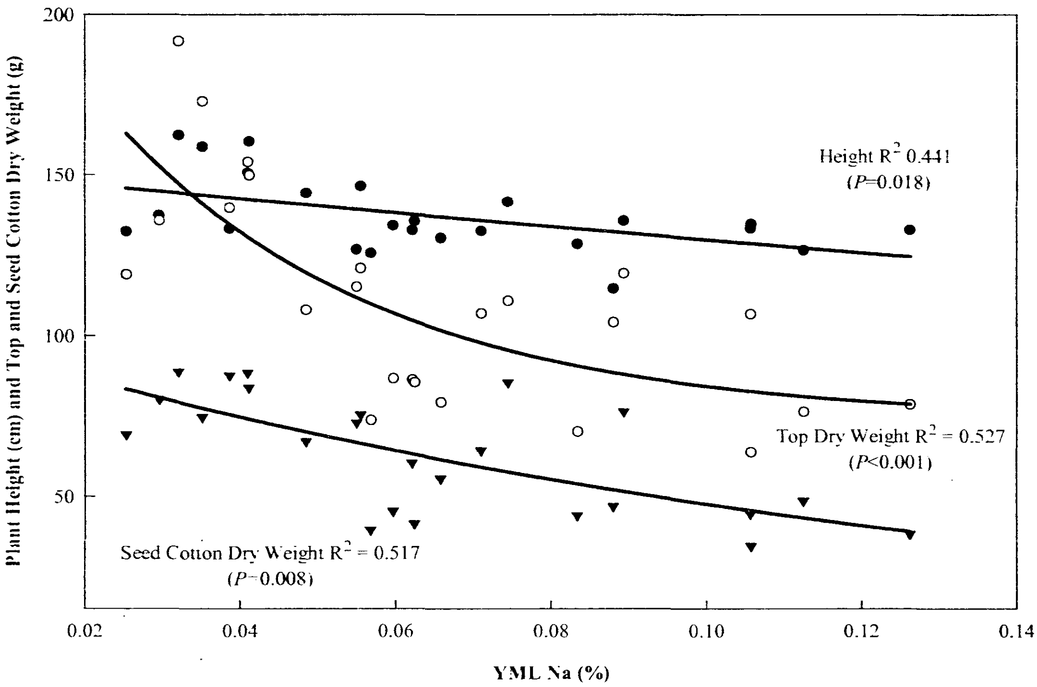
The results of this experiment demonstrate that both the physical and chemical characteristics of sodic soils have a negative effect on the dry matter accumulation and lint yield of cotton grown to maturity. In this Grey Vertosol, the physical effects of sodicity were dominant in reducing cotton performance, at ESP levels up to 20%, masking any chemical effects of sodicity. At ESP values >20% however, the gap between the dry matter accumulation of the control and PAM treatments narrowed and PAM amendment did not significantly improve lint yield, indicating that soil chemical factors significantly reduced plant performance at these sodicity levels.

The physical properties of sodic soils that may limit crop performance include high bulk density, uneven soil wetting and an increased incidence and severity of waterlogging events. These properties in turn, may reduce the ability of the plant to access soil water and nutrients by reducing root growth and impairing root function through extending the time during which the soil is beyond the non-limiting water range (NLWR) for cotton growth. In particular, the physical condition of sodic soils in this experiment were found to reduce the availability of K to levels that may limit plant growth and to increase plant Na uptake to levels significantly higher than those resulting directly from soil solution chemistry.

The chemical properties of sodic soil that may limit crop performance include high concentrations of soil solution Na and reductions in the availability of nutrients due to increases in soil pH. Although no direct causal relationship was established between cotton Na concentrations and lint yield reductions, the results of this experiment indicate that mid-season YML Na concentration greater than approximately 0.08% could significantly limit cotton crop performance, if not confounded by the effects of poor soil physical condition. Boron and manganese availability were also borderline in the most sodic PAM-amended soils. It is possible that a combination of the limited availability of these nutrients and high Na availability contributed to the reduced performance of cotton at high ESP levels, despite the amelioration of physical limitations in the PAM treatments. The reduced plant dry matter accumulation that occurred in the control treatments as a result of poor soil physical condition reduced the B stress placed upon the plants at highest ESP level.

It is clear that soil physics has a strong influence on the productivity of cotton crops in sodic soils. The relative contributions of high soil strength and soil anoxia to the physical effects of sodic soils on cotton were not however resolved in this experiment. The relative importance of the drier and wetter ends of the soil moisture range in limiting the productivity of cotton crops is likely to vary according to individual soil characteristics and management factors.

Figure 5-2 The relationships between the mid-season youngest mature leaf sodium and potassium concentrations of cotton (Gossypium hirsutum L.) produced on a Grey Vertosol and plant height, shoot dry weight and seed cotton yield.



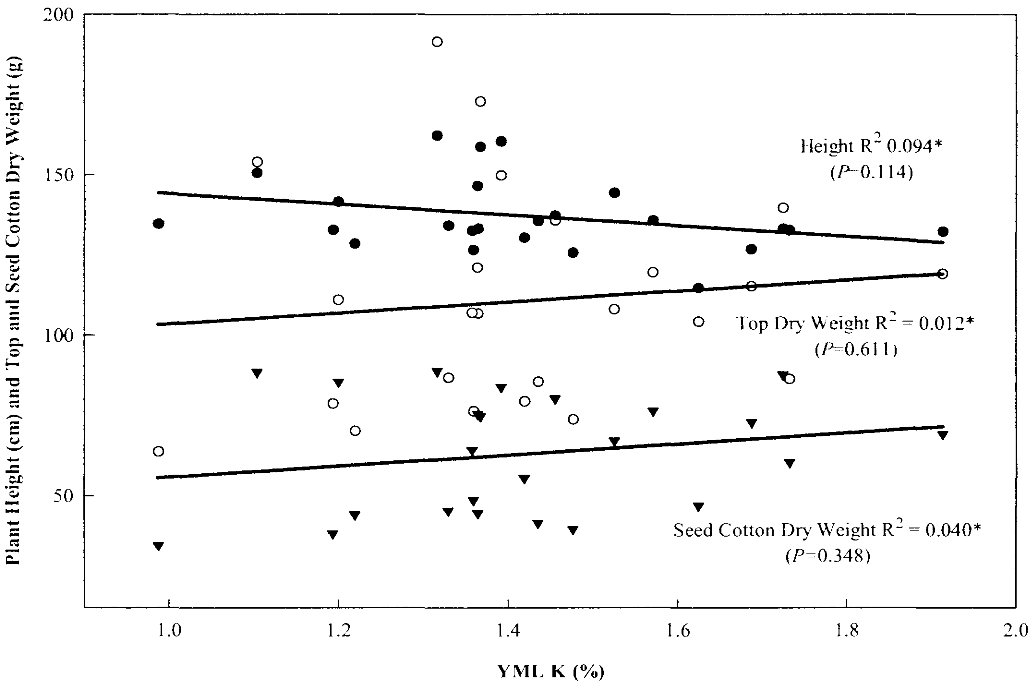
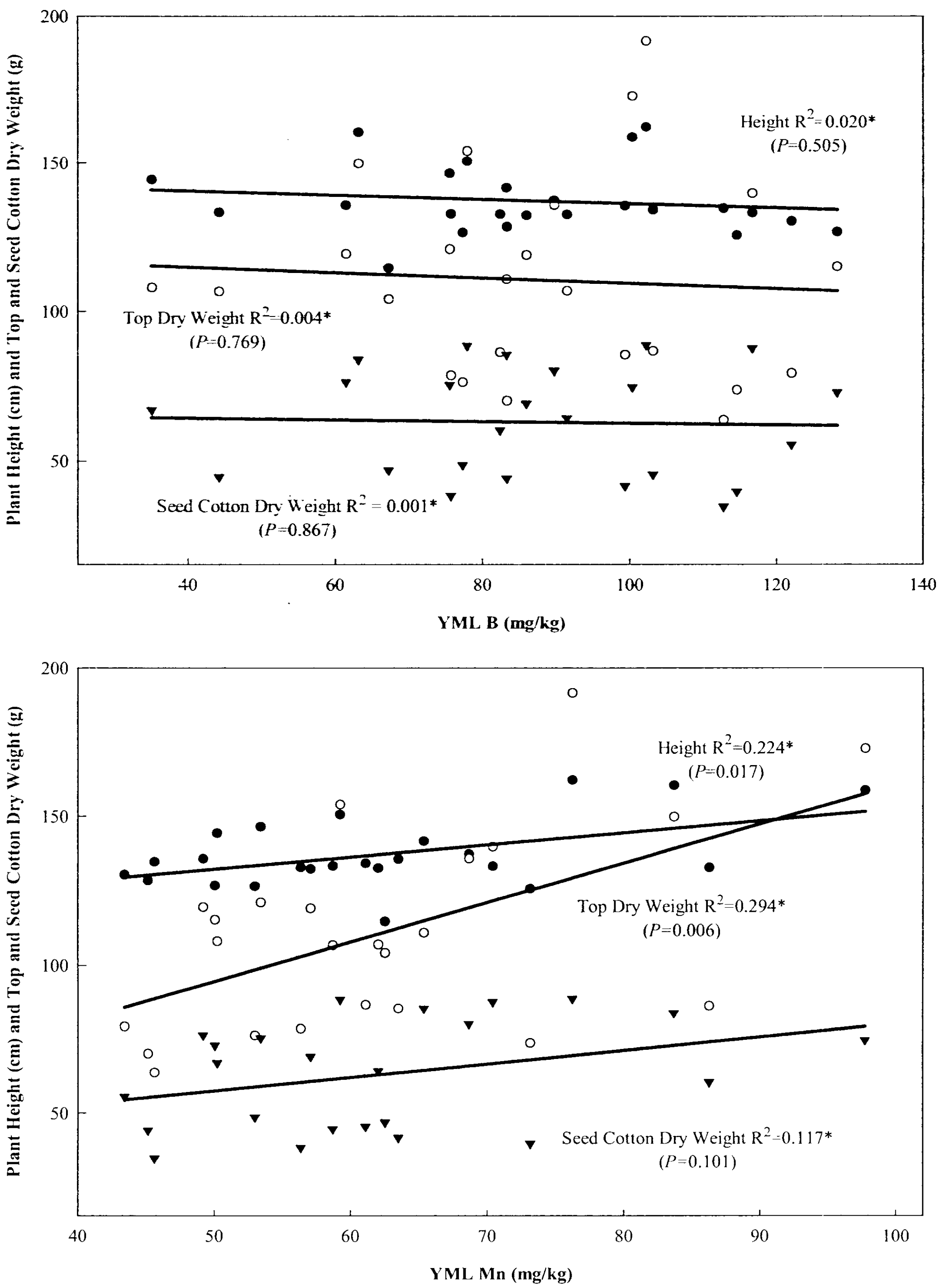


Figure 5-3 The relationships between the mid-season youngest mature leaf boron and manganese concentrations of cotton (Gossypium hirsutum L.) produced on a Grey Vertosol and plant height, shoot dry weight and seed cotton yield.



Chapter 6. The effect of waterlogging on cotton (*Gossypium hirsutum* L.) growth and nutrition in sodic soils

6.1. Introduction

The dispersive nature of sodic soils can result in low levels of macroporosity and thus reduced soil hydraulic conductivity. Crops produced on sodic soils frequently suffer aeration stress after irrigation or rainfall events (Jayawardane and Chan 1994) as restricted water intake results in waterlogging in the surface soil layers and restricted internal drainage results in waterlogging in sodic subsoils (McIntyre 1979; McIntyre *et al.* 1982).

When a soil becomes waterlogged, the pore space in the soil structure that usually allows the exchange of gas between the soil and atmosphere is filled with water and diffusion of oxygen is limited. In warm conditions where there is an adequate supply of labile carbon, root and micro-organism respiration can then totally deplete the soil of oxygen within a 24 h period and a build up of CO_2, and possibly ethylene and H_2S occurs (Trought and Drew 1980b). Hence, waterlogging can reduce root growth, kill root apices and change the patterns of nutrient accumulation by plants (Trought and Drew 1980b; c; d). Plants grown under aerobic conditions actively accumulate K and P and partially exclude Na over a wide range of Na concentrations. Under anoxic conditions however, membrane selectivity for K and P and exclusion of Na are compromised, due to a rapid decline in root ATP levels (Drew and Dikumwin 1985; Drew and Lauchli 1985).

Plants grown in sodic fields have significantly higher levels of Na and lower levels of P in their tissues (Chapter 2) than those produced under sodic conditions in the glasshouse (Chapter 5). Specifically, the plants grown to maturity in soil with an ESP of 24% in the glasshouse experiment described in Chapter 5, accumulated harvest YML Na concentrations of 0.21% (Table 5-4) and harvest YML P concentrations of 0.46% (Table 5-6). In the field experiment described in Chapter 2, soil with an ESP of 24% produced cotton with harvest YML Na concentrations of approximately 0.48% (Figure 2-7) and harvest YML P concentrations of approximately 0.30% (Figure 2-9). Additionally in the field cotton P concentrations and uptake were negatively affected by soil sodicity (Figure 2-9) while in the glasshouse no significant relationship between sodicity and cotton P concentrations was measured (Table 5-6). One factor that contributed to the discrepancy between the P results of these two experiments was the P concentrations of the soils; the soils used in the glasshouse experiment had uniformly high P fertility (42 mg/kg) and the soils in the field that produced plants with the lowest P concentrations had soil P concentrations bordering on the critical concentration of 6 mg/kg (Dorahy *et al.* 2002). It is also hypothesized however, that an increased frequency and/or severity of waterlogging events in field situations contributed to the discrepancies between the results of these two experiments. The differential response of soils to potential waterlogging events, according to their sodicity level may be due to both physical and chemical soil factors; sodic soils may be more susceptible to suffering more frequent and/or more extended waterlogging events due to their poor physical condition and the rate of recovery of plants from waterlogging may be slower in sodic soils due to increased levels of root damage occurring under conditions of high soil solution Na. Understanding the effect of anoxic soil solution conditions on nutrient uptake and plant growth and its interaction with high levels of soil Na may help to explain poor growth of cotton in sodic fields.

This chapter concerns a glasshouse experiment growing cotton in a Grey Vertosol with an artificially created range of sodicity levels (ESP 2-25%), with and without the inclusion of a 7-day period of waterlogging. Labelled ^{32}P was applied to the soils after waterlogging to assess the effect of sodicity on the rate of recovery of cotton roots. The effects of waterlogging on nutrient accumulation at different levels of soil sodicity were assessed through plant tissue nutrient analysis.

6.2. Methods

6.2.1. *Soil preparation*

The soil used in this experiment was collected from a cotton field at the Australian Cotton Research Institute, Myall Vale, NSW (150°E, 30°S), where it had been used for irrigated cotton and wheat cropping for approximately 25 years. The soil was a fertile dark greyish brown cracking clay, classified as a fine, thermic montmorillonitic Typic Haplustert (Soil Survey Staff, 1996) or a Grey Vertosol (Isbell 1996). Selected soil properties are presented in Appendix 1.

Sodification treatments were applied to 50 kg batches of the soil according to the method outlined in Chapter 2, in order to create soils that varied primarily in their exchangeable Na and Ca content, whilst maintaining soil properties that are independent of ESP. The soil was equilibrated with treatment solutions varying in SAR (0, 45, 100 and 200) and with the major nutrient cations Ca, Na, Mg and K included as Cl salts. Excess salt was removed from each treatment by equilibration of the soil with solutions of equivalent SAR but lower total cation concentrations. The experiment consisted of four ESP treatments (~2.4, 12.1, 16.2 and 24.8%) with six 2.5 kg replicates of each treatment.

6.2.2. *Soil chemical analysis*

A sample of each soil was ground to pass through a 2 mm sieve. Soil cation exchange capacity (CEC) determination can be time-consuming and costly and thus it is rarely directly measured. Instead, an effective cation exchange capacity (ECEC) was calculated based upon the quantities of exchangeable Ca, Mg, K and Na in the soil. The ECEC and cation composition of each soil was analysed using a modified version of the method outlined by Tucker (1972), as this method minimises the impact of soil carbonate on exchangeable Ca determination. A 2 g sample of each soil was weighed into a plastic centrifuge tube and 40 mL of 1M NH_4Cl (buffered to pH 8.5) was added. The tubes were shaken end-over-end for 1 h, centrifuged for 15 min at 3000 rpm (2010 *g*) and the supernatant filtered using Whatman No.1 paper and analysed using inductively coupled plasma atomic emission spectroscopy (ICPAES).

Corrections for soluble salts were made according to the method of So *et al.* (2004), rather than using an ethanol pre-wash. A 150 g sample of the soil was raised to field capacity with deionised water, covered with wet paper towelling and allowed to equilibrate for 48 h in a closed container. The soil solution was extracted by centrifuging the soil for 30 min at 4000 rpm (3580 g), filtered to 0.22 μm (Millipore Pty Ltd) and salts determined using ICPAES. Exchangeable cations were calculated as the difference between the NH_4Cl-extracted cations and soil solution cations.

The pH and electrical conductivity (EC) of the soils were analysed in a 1:5 water suspension. An additional analysis of pH was carried out in a matrix of Na and Ca added as chloride salts, in quantities to produce concentrations similar to that found in the soil solution. The $EC_{1:5}$ values were converted to the electrical conductivity of the saturated extract (EC_{se}) using a conversion factor for heavy clays of 5.8 (Slavich and Petterson 1993), to assist the interpretation of the results in terms of plant growth thresholds.

6.2.3. *Experimental design*

The experiment was a randomised block design, with cotton grown in 48 pots containing soils of four sodicity levels. Two watering regimes were applied during the experiment, including a control treatment that was maintained at field capacity and a waterlogging treatment that was inundated for a period of 7 days. Two replicates of each sodicity and waterlogging treatment were harvested immediately after the waterlogging event and the remaining four harvested two weeks later.

6.2.4. *Experimental methods*

This experiment was carried out in a glasshouse situated at the University of New England, Armidale, Australia. The temperature in the glasshouse was maintained within the range of 20 to 35°C. Before planting, fertiliser was incorporated into the soil for each replicate: 100 kg/ha of N as urea and mono-ammonium phosphate (MAP), 10kg /ha of P as MAP and 1 kg /ha of Zn as $ZnSO_4$. The soil for each replicate was then weighed into pots 25 cm in height and 10 cm in diameter.

Initially the soil and pot were weighed and the soil brought to field capacity (~ 42% w/w). Ten cotton seeds (cv Sicot 289BR, CSD Pty Ltd) were planted into each pot and the pot covered with plastic to prevent excessive evaporation and hard-setting of the soil. Upon the cotton reaching the two-leaf stage the plastic was removed and the plants thinned to six per pot.

Throughout the first 4 weeks of the experiment each pot was watered by weight with deionised water to field capacity every second day. When the plants had reached a height of 20 cm six pots of each ESP treatment were waterlogged by placing them in a 10 L plastic bucket filled with deionised water. The remaining replicates continued to be watered by weight to field capacity every day. After a 7-day period the inundated pots were removed from the buckets and allowed to drain. Two replicates from each ESP and watering regime treatment were harvested by cutting the plant stems just above the soil level. The control pots continued to be watered by weight to field capacity and this process was reapplied to the waterlogging pots, once field capacity was reached.

6.2.5. *^{32}P Preparation and application*

A 0.37 MBq/mL solution of labelled P was made by diluting 74 MBq of ^{32}P in 200 mL of deionised water. A total of 1.85 MBq was added to each pot immediately following the waterlogging event. To apply the isotope to the soil, 5 fine holes were placed in each pot to a depth of 10 cm with a metal skewer approximately 3 mm in diameter. In each hole, 1 mL of labelled P was applied with a syringe. The uptake of the ^{32}P by the cotton plants was assessed daily by placing a Geiger counter on the youngest mature leaves (YMLs), with the rest of the plant shielded behind a Perspex screen.

6.2.6. *Plant harvest and nutrient determination*

Fourteen days after the removal of the waterlogging treatment all remaining plants were harvested by cutting the stems just above the soil surface. All plant material was dried in a fan-forced oven at 80^0C, weighed, ground to <2 mm and digested with perchloric acid and hydrogen peroxide, using the sealed chamber method outlined by Anderson and Henderson (1986). The nutrient composition of the samples was determined using ICPAES. An Australian Soil and Plant Analysis Council (ASPAC) sample was included in the analyses to ensure the accuracy of the digestion process.

In order to determine the ^{32}P concentrations of the samples, scintillant was prepared according to the method of Till *et al.* (1984): 16.92 g of p-terphenyl and 0.73 g of POPOP was added to 1 L toluene and heated until dissolved. This solution was then added to 2080 mL Teric in a 5 L flask and made to volume with toluene when cooled. A 1 mL aliquot of digested cotton tops was added to a 20 mL scintillation vial with 17 mL of scintillant and thoroughly mixed. The samples were counted in a United Technologies Packard Tri-carb 2000 Liquid Scintillation Analyser (LSC). Counting time was 10 minutes in a counting channel between 5 and 1700 kev. Radioactivity from ^{32}P was calculated using by subtracting background radiation (cpm) from a blank vial to obtain net counts of ^{32}P per minute. This was multiplied by the counting efficiency (determined from a vial spiked with 1% of the stock solution) and corrected for radioactive decay to establish Bq/g of plant sample.

6.2.7. *Statistical analysis*

The replicates in this experiment were arranged in a randomised block design. Analyses of variance (ANOVA) were used to test the significance of treatment differences ($P<0.05$), with soil sodicity and waterlogging as factors, and two replicate plants per treatment at the initial harvest date and four plants per treatment at the final harvest date. Repeated measures analysis was not necessary as destructive sampling of two representative replicates was used to establish baseline nutrient concentrations. Where significant interactions between the effects of sodicity and the effects of waterlogging were found, differences between individual treatment combinations were further evaluated by least significant difference (LSD) ($P<0.05$) and these values used to inform the labelling of the tables of results with indicators of significance. A separate ANOVA with nutrient solution SAR as the factor and 6 replicate soils was carried out determine the effect of the sodification procedure on the resultant chemical characteristics of the soil. An additional separate ANOVA, with soil sodicity as the factor and 4 replicate plants, was carried out to test the significance of sodicity on the rate at which the pots returned to field capacity after waterlogging. Statistical analyses were carried out using the Genstat program (7th Edition, Lawes Agricultural Trust) (Payne 1987).

In this analysis, each individual pot was designated as a replicate, despite the treatment of each of the soils within a given sodicity treatment in one equilibration procedure. The use of individual pots as replicates was a valid approach in this experiment, as the aim of the experiment was to assess the response of cotton plants to sodicity and waterlogging. It was believed that the most significant within-treatment variation in this system was derived from genetic variation between individual cotton plants and temperature, moisture and light variation between the different pots, validating the use of individual pots as treatment replicates.

6.3. Results

6.3.1. *Soil characteristics*

Soil sodification produced ESP values ranging from 2 to 25% (P<0.001) but without significantly changing ECEC (P=0.61), which ranged between 38 to 39% (Table 6-1). The exchangeable Ca and Mg concentrations of the soil decreased significantly with increasing sodicity (P<0.001) but there was no significant difference in exchangeable K between the soils (P=0.11). The pH of the soil increased significantly with increasing soil sodicity (P<0.001) but the magnitude of this increase was reduced when the analysis was carried out in a matrix of Na and Ca salts. There was no significant difference in the EC of the soils among the four sodicity treatments (P=0.11).

Table 6-1 The effect of equilibration solution sodium absorption ratio on the cation content, effective cation exchange capacity, exchangeable sodium percentage, pH and electrical conductivity of a Grey Vertosol. Values are means of six replicates ± standard errors.

Sol^n SAR	Ca (cmol/kg)	Mg (cmol/kg)	K (cmol/kg)	ECEC (cmol/kg)	ESP (%)	pH (H_2O)	pH (SoilSol^n)	EC (dS/m)
0	27.2 ± 0.3	9.8 ± 0.2	1.5 ± 0.02	38.0 ± 0.4	2.4 ± 0.1	7.6 ± 0.03	7.3 ± 0.02	2.7 ± 0.2
45	25.3 ± 0.3	9.8 ± 0.2	1.6 ± 0.03	39.1 ± 0.7	12.1 ± 0.5	8.3 ± 0.03	7.6 ± 0.03	2.7 ± 0.2
100	23.5 ± 0.2	8.9 ± 0.1	1.6 ± 0.01	38.6 ± 0.5	16.2 ± 0.4	8.5 ± 0.04	7.9 ± 0.02	2.8 ± 0.1
200	21.2 ± 0.5	8.1 ± 0.0	1.5 ± 0.04	38.6 ± 0.7	24.8 ± 0.4	8.7 ± 0.04	7.9 ± 0.04	2.8 ± 0.3

6.3.2. *Cotton dry matter accumulation*

Increasing soil sodicity reduced the dry matter accumulation of cotton at the initial harvest (P=0.05) (Table 6-2). At the final harvest, cotton dry matter accumulation was also significantly affected by ESP (P<0.001), decreasing by 19% between the 2% and 25% ESP treatments, when averaged over waterlogging regimes. No significant difference in dry matter accumulation between the control and waterlogged treatments was measured at any sodicity level either immediately after the waterlogging event or following the 2-week recovery period and there were no significant interactions between the effects of sodicity and the effects of waterlogging on cotton dry matter accumulation ($P>0.05$).

6.3.3. *Cotton water use*

The average daily water use of cotton was reduced in the higher soil sodicity treatments ($P<0.001$) (Table 6-2). Sodicity had no effect on the rate at which the waterlogged pots returned to field capacity ($P=0.91$), as all treatments returned to field capacity within 5 days. Subjecting the cotton plants to a period of waterlogging also reduced their average daily water use ($P=0.001$) but there was no significant interaction between sodicity and waterlogging on the water use of the cotton plants ($P=0.13$).

Table 6-2 The effect of sodicity and waterlogging on the dry matter accumulation and daily water use of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol and time taken for the soil to return to field capacity after waterlogging. Initial values are means of two replicates ± standard errors. Harvest dry weight and water use values are means of four replicates ± standard errors. ns designates no significant interaction between the effects of sodicity and the effects of waterlogging.

Treatment	ESP (%)	Initial Dry Weight (g)	Harvest Dry Weight (g)	Average Daily Water Use (mL/Day)	Time to Return to Field Capacity (Days)
Control	**2**	8.4 ± 0.6	21.8 ± 0.2	149 ± 5	N/A
	12	7.6 ± 0.4	19.1 ± 0.0	151 ± 8	N/A
	16	7.9 ± 0.7	19.3 ± 0.3	115 ± 13	N/A
	25	6.2 ± 0.5	17.9 ± 0.6	97 ± 3	N/A
Waterlogging	**2**	8.7 ± 0.2	21.8 ± 0.0	132 ± 5	4.5 ± 0.3
	12	8.0 ± 1.0	19.3 ± 0.2	112 ± 6	4.3 ± 0.8
	16	8.6 ± 0.1	18.6 ± 0.4	109 ± 6	4.8 ± 0.3
	25	7.4 ± 0.4	17.5 ± 1.1	85 ± 5	4.5 ± 0.5
LSD		*ns*	*ns*	*ns*	*N/A*

6.3.4. *Rate of cotton root recovery from waterlogging*

Uptake of labelled P was observed 2 days after application in the aerated non-sodic pots and at increasing intervals with increasing soil sodicity ($P<0.001$) (Table 6-3). The time taken for uptake of labelled P to be observed increased by 225% in the control treatments and by 183%

in the waterlogging treatments, as soil ESP increased from 2 to 25%. Waterlogging also delayed the uptake of labelled P ($P<0.001$). There was a significant interaction between sodicity and waterlogging on the time taken for uptake of labelled P to be observed ($P<0.001$), with the effect of waterlogging being most significant in the moderately sodic soils.

The time to reach a Geiger counter reading of 2 counts/s increased with increasing soil sodicity ($P<0.001$) and ($P<0.001$). There was no significant interaction between the effects of sodicity and the effects of waterlogging on the time taken to reach the Geiger counter reading of 2 counts/s ($P>0.05$).

Table 6-3 The effect of sodicity and waterlogging on the time before ^{32}P uptake was observed and the time taken to reach a Geiger counter reading of two counts/s in the youngest mature leaves of cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of four replicates ± standard errors. Within columns values with the same letters do not differ significantly ($P<0.05$) and ns designates no significant interaction between the effects of sodicity and the effects of waterlogging

Treatment	ESP (%)	Time Before ^{32}P Uptake Observed (Days)	Time to Reach Geiger Reading of 2 counts/s (Days)
Control	2	2.0 ± 0.0 [a]	3.8 ± 0.9
	12	3.5 ± 0.3 [a]	6.0 ± 0.4
	16	3.5 ± 0.6 [a]	7.8 ± 0.3
	25	6.5 ± 1.0 [b]	8.5 ± 0.3
Waterlogging	2	3.0 ± 0.4 [a]	7.3 ± 1.1
	12	8.3 ± 0.5 [bc]	9.5 ± 1.0
	16	9.3 ± 0.5 [c]	10.5 ± 0.3
	25	8.5 ± 0.9 [c]	11.0 ± 1.0
LSD		*1.8*	*ns*

6.3.5. ^{32}P Concentrations and total accumulation

Both increasing soil sodicity and waterlogging decreased the concentrations ($P<0.001$) and total accumulation ($P<0.001$) of ^{32}P in the cotton plants (Table 6-4). There were however significant interactions between sodicity and waterlogging on the concentrations ($P=0.05$) and accumulation ($P=0.04$) of ^{32}P in the cotton plants. The effects of sodicity on the concentrations and accumulation of labelled P were apparent in only the 25% ESP level in the control treatment but also in the 16% ESP level in the waterlogged treatments.

Table 6-4 The effect of sodicity and waterlogging on the concentration and total accumulation of ^{32}P in cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Values are means of four replicates ± standard error. Within columns values with the same letters do not differ significantly ($P<0.05$).

Treatment	ESP (%)	^{32}P Concentration (Bq/g)	^{32}P Uptake (kBq)
Control	2	2690 ± 143 ^{b}	58.7 ± 3.6 ^{a}
	12	3310 ± 185 ^{a}	63.3 ± 3.5 ^{a}
	16	2680 ± 337 ^{b}	51.8 ± 6.6 ^{ab}
	25	1690 ± 196 ^{cd}	29.9 ± 2.5 ^{de}
Waterlogging	2	2050 ± 211 ^{c}	44.7 ± 4.6 ^{bc}
	12	2010 ± 152 ^{c}	38.6 ± 2.7 ^{cd}
	16	1400 ± 84 ^{d}	25.9 ± 1.1 ^{e}
	25	1540 ± 286 ^{cd}	25.9 ± 4.6 ^{e}
LSD		*578*	*11.6*

6.3.6. Nutrient concentrations and accumulation

Sodium

Cotton plant Na concentrations and total accumulation increased with increasing soil sodicity in both the control and waterlogged treatments, at the first and second harvest dates ($P<0.001$) (Table 6-5). Cotton plants in the waterlogging treatments contained higher Na concentrations both immediately ($P=0.003$) and 2 weeks after ($P<0.001$) the waterlogging period and accumulated more Na between the initial and final harvest date ($P<0.001$). At the final harvest date, waterlogging increased cotton Na concentrations by an average of 28% and Na accumulation by an average of 40%, across the range of ESP levels.

There were significant interactions between sodicity and waterlogging on the initial ($P=0.05$) and final ($P=0.01$) Na concentrations of the cotton plants and on the accumulation of Na between the initial and final harvest dates ($P=0.002$). Waterlogging affected cotton Na concentrations only in the 12% ESP treatment at the initial harvest date and only in the highest ESP treatments (16% and 25%) at the final harvest date. Similarly, waterlogging affected cotton Na accumulation only in the 16% and 25% ESP treatments.

Table 6-5 The effect of sodicity and waterlogging on the concentration and total accumulation of sodium by cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Initial concentrations are means of two replicates ± standard errors. Remaining values are means of four replicates ± standard errors. Within columns values with the same letters do not differ significantly ($P<0.05$).

Treatment	ESP (%)	Na Concentrations (%)		Na Accumulation Between Initial and Final Harvest Dates (mg)
		Initial	Final	
Control	**2**	0.04 ± 0.00 [a]	0.06 ± 0.00 [a]	8.4 ± 0.7 [a]
	2	0.19 ± 0.01 [b]	0.19 ± 0.02 [b]	17.4 ± 1.5 [b]
	16	0.25 ± 0.01 [c]	0.22 ± 0.00 [b]	21.8 ± 0.5 [b]
	25	0.50 ± 0.05 [e]	0.41 ± 0.02 [d]	39.0 ± 2.3 [c]
Waterlogging	**2**	0.05 ± 0.00 [a]	0.06 ± 0.00 [a]	9.4 ± 0.5 [a]
	12	0.31 ± 0.04 [d]	0.22 ± 0.01 [b]	20.6 ± 1.7 [b]
	16	0.29 ± 0.02 [cd]	0.34 ± 0.01 [c]	37.7 ± 3.1 [c]
	25	0.54 ± 0.01 [e]	0.58 ± 0.04 [e]	61.2 ± 8.0 [d]
LSD		*0.05*	*0.06*	*9.5*

Potassium

Increasing soil sodicity decreased the K concentrations of cotton at both the first (P=0.003) and second harvest dates (P<0.001) (Table 6-6). The total K accumulation of cotton between the initial and final harvests also decreased with higher sodicity (P<0.001).

Waterlogging decreased the cotton K concentrations at both the initial (P=0.01) and final (P<0.001) harvests and reduced the accumulation of K by the cotton plants during this period (P<0.001). At the final harvest, waterlogging reduced cotton K concentrations by an average of 8% and K accumulation by an average of 18%, across the range of ESP levels. There was however a significant interaction between sodicity and waterlogging on the cotton K concentrations at the final harvest (P=0.03), with the greatest effect of waterlogging on the final K concentrations occurring in the 12% ESP treatments.

Table 6-6 The effect of sodicity and waterlogging on the concentration and total accumulation of potassium by cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Initial concentrations are means of two replicates ± standard errors. Remaining values are means of four replicates ± standard errors. Within columns values with the same letters do not differ significantly (P<0.05) and ns designates no significant interaction between the effects of sodicity and the effects of waterlogging.

Treatment	ESP (%)	K Concentration (%) Initial	K Concentration (%) Final	K Accumulation Between Initial and Final Harvest Dates (mg)
Control	2	1.68 ± 0.02	1.25 ± 0.05 ab	129.9 ± 9.1
	12	1.71 ± 0.03	1.31 ± 0.03 a	139.8 ± 6.5
	16	1.64 ± 0.06	1.16 ± 0.01 cd	106.3 ± 4.2
	25	1.44 ± 0.01	1.09 ± 0.03 cd	90.6 ± 3.6
Waterlogging	2	1.53 ± 0.00	1.17 ± 0.03 bc	123.1 ± 5.0
	12	1.54 ± 0.00	1.11 ± 0.03 cd	106.3 ± 4.4
	16	1.61 ± 0.01	1.08 ± 0.01 d	63.6 ± 3.9
	25	1.33 ± 0.04	1.07 ± 0.01 d	87.9 ± 11.2
LSD		*ns*	*0.08*	*ns*

Phosphorus

Waterlogging significantly reduced the P concentrations of cotton at both the initial and final harvest date and the total accumulation of P during this period ($P<0.001$) (Table 6-7). At the final harvest, waterlogging reduced cotton P concentrations by an average of 20% and P accumulation by an average of 28%, across the range of ESP levels.

At the initial harvest, sodicity significantly reduced the P concentrations of cotton ($P=0.01$) but the interaction between sodicity and waterlogging on initial cotton P concentrations was also significant ($P=0.03$). There was no overall correlation between soil sodicity and cotton P concentrations in the control treatments, but the 16% ESP treatment had a higher P concentration than the non-sodic soil. In contrast, cotton P concentrations tended to decrease with higher soil sodicity in the waterlogging treatments. Additionally, the negative effect of waterlogging on initial cotton P concentrations was only significant in the moderately sodic soils.

At the final harvest there was no significant effect of sodicity on cotton P concentrations ($P=0.10$) but waterlogging decreased the accumulation of P by the cotton plants ($P<0.001$). There were no significant interactions between sodicity and waterlogging on the final cotton P concentrations or the accumulation of P between the initial and final harvest ($P>0.05$).

Table 6-7 The effect of sodicity and waterlogging on the concentration and total accumulation of phosphorus by cotton (*Gossypium hirsutum* L.) produced on a Grey Vertosol. Initial concentrations are means of two replicates ± standard errors. Remaining values are means of four replicates ± standard errors. Within columns values with the same letters do not differ significantly (P<0.05) and ns designates no significant interaction between the effects of sodicity and the effects of waterlogging.

Treatment	ESP (%)	P Concentrations (%) Initial	P Concentrations (%) Final	P Accumulation Between Initial and Final Harvest (mg)
Control	2	0.12 ± 0.00 ^{bc}	0.13 ± 0.00	17.1 ± 0.8
	12	0.13 ± 0.01 ^{ab}	0.13 ± 0.01	16.7 ± 1.0
	16	0.15 ± 0.00 ^{a}	0.12 ± 0.00	13.5 ± 0.4
	25	0.12 ± 0.00 ^{cd}	0.12 ± 0.01	12.0 ± 0.4
Waterlogging	2	0.12 ± 0.00 ^{cd}	0.10 ± 0.00	12.2 ± 0.6
	12	0.11 ± 0.00 ^{de}	0.10 ± 0.00	11.3 ± 0.5
	16	0.11 ± 0.00 ^{de}	0.10 ± 0.00	8.8 ± 0.5
	25	0.10 ± 0.00 ^{e}	0.10 ± 0.00	10.0 ± 1.1
LSD		*0.01*	*ns*	*ns*

6.4. Discussion

6.4.1. *Cotton dry matter accumulation*

Soil sodicity reduced the growth of cotton plants produced in Grey Vertosols, even at low ESP levels, from as early as 8 weeks after planting (Chapter 5; Table 5-1). While this experiment was harvested after only 7 weeks of plant growth, there were significant reductions in dry matter accumulation at the final harvest date with increasing soil sodicity, in both the control and waterlogging treatments.

Waterlogging also reduces dry matter accumulation in mature cotton plants (Bange *et al.* 2004; Hocking *et al.* 1987; McLeod 2001). Immediately after a waterlogging event, anaerobic conditions reduced the shoot dry weight of maize seedlings (Drew and Dikumwin 1985) but slightly increased the shoot dry weight of young wheat plants, due to reduced translocation of photosynthate to the roots (Trought and Drew 1980d). No effect of waterlogging on the early-season dry matter accumulation of cotton has been reported in field experiments (Hodgson 1982). It was therefore expected that no effect of waterlogging on the dry matter accumulation of cotton would be observed in this experiment, given the early stage of plant growth and relatively small increases in dry matter during the experimental period.

6.4.2. *Cotton water use*

The daily water use of each pot in this experiment was estimated by weight. The limitation of this method is that it measures moisture lost through both transpiration and evaporation. The small size and relatively high surface area: volume ratio of the pots used in this experiment mean that it is likely that evaporation contributed significantly to the average daily water use figures, making it difficult to determine treatment differences in transpiration alone. Sodicity did not significantly increase the time taken for the waterlogged pots to drain to field capacity, which suggests that the duration of the waterlogging event was not extended in the more sodic soils. Sodicity did however delay the uptake of ^{32}P in the waterlogged soils (Table 6-3), which suggests that the waterlogging event may have been prolonged with higher soil sodicity. It is possible, that increasing soil sodicity decreased the rate at which soil O_2, CO_2 and possibly ethylene concentrations returned to normal levels, despite the return of optimum soil water contents, due to the reduced macroporosity associated with sodic soils (McIntyre 1979). The O_2, CO_2 and ethylene contents of the soils in this experiment were not measured.

Soil sodicity reduced the average daily water use of the cotton plants in this experiment. The adverse physical condition of the soils with increasing sodicity may have reduced evaporative losses through the formation of a surface seal. It is unclear if reductions in plant transpiration contributed to these patterns of average daily water use but as increasing soil sodicity decreased harvest dry matter accumulation (Table 6-2), it is likely that there was also a negative effect on transpiration. Waterlogging also significantly reduced the average daily water use of cotton plants, which illustrates the effect of waterlogging on plant function, across the range of sodicity levels.

6.4.3. *Rate of cotton root recovery from waterlogging*

The aim of monitoring the ^{32}P uptake of the cotton in the different treatments, using a Geiger counter, was to determine root recovery time of the cotton in the different sodicity treatments after waterlogging, with labelled P uptake indicating root activity. Labelling of the soil with ^{32}P was an appropriate way to measure the recovery of roots from anaerobic soil conditions, as healthy, functioning and actively growing plants would accumulate greater amounts of isotope.

Soil sodicity increased the time taken for the cotton plants to begin to accumulate labelled P and the time taken for the cotton plants to reach a Geiger counter reading of 2 counts/s, in both the control and waterlogged soils. These effects were larger in the control than in the waterlogged soils, highlighting the importance of the poor soil physical condition of sodic soils on root growth and activity, even at field capacity. This result is supported by the results of the experiment described in Chapter 5, where the adverse physical condition of sodic soils reduced the dry matter accumulation and K concentrations of cotton, even where soil water was managed carefully.

The cotton plants exposed to a period of waterlogging took more time to begin to accumulate labelled P than those in the control treatments, in the moderately sodic soils. This trend continued throughout the experiment, with time taken to reach a Geiger counter reading of 2 counts/s increasing across the range of sodicity levels following exposure to a waterlogging event. In the non-sodic soils waterlogging did not affect the rate at which the plants recovered their growth and activity immediately after the waterlogging event but it did reduce their function in the subsequent fortnight. In the highly sodic soils, the poor physical condition of soil limited to the growth and activity of the roots under conditions of optimum water content, so that waterlogging did not affect the rate at which the plants recovered their growth and activity after the waterlogging event but it did reduce their function in the subsequent fortnight. In the moderately sodic soils waterlogging reduced the growth and/or functioning of the cotton roots such that they accumulated labelled P more slowly than the plants in the control treatments.

The commencement of labelled P uptake by the plants in the waterlogging treatments in the 2-week period following inundation indicates that the roots recovered some function. No compensation was measured however, for the reduced rates of uptake measured immediately after the waterlogging event. Given a longer period of optimum soil water conditions, the plants in waterlogged treatments may have compensated for the reduced P accumulation during the waterlogging event. During the boll-filling period of the cotton growth season however, irrigation intervals can be as short as 5-6 days, which given the results of this experiment, is insufficient time for compensatory P accumulation. It is important to note however, that the root distribution and P demand of more mature cotton plants are considerably different to those of cotton seedlings. Further experimentation would need to be carried out to accurately assess the capacities of more mature cotton plants to compensate for reduced P accumulation following waterlogging. The Geiger counter results of this experiment illustrate that sodicity directly reduced cotton plant function across the range of ESP treatments and in field production situations, an increase in the frequency and/or duration of waterlogging events with increasing soil sodicity may exacerbate this effect, especially in moderately sodic soils.

6.4.4. *^{32}P Concentrations and accumulation*

The concentrations of ^{32}P measured in the plants of the control treatments illustrate the effects of sodicity on cotton plant function at field capacity. The cotton concentrations and accumulation of labelled P were not significantly reduced by moderate soil sodicity, but at an ESP of 25% concentrations and accumulation of labelled P were reduced. This result reflects those obtained using the Geiger counter; the time taken for uptake of labelled P to begin was significantly reduced by soil sodicity at an ESP of 25% in the control treatment.

The decrease in the rate of ^{32}P uptake in the most sodic soil of the control treatments contrasts with the unlabelled P results obtained both in this experiment (Table 6-7) and the experiment described in Chapter 5 (Table 5-5). Both of these experiments determined that there was no decrease in plant P concentrations with soil sodicity despite the adverse physical and chemical conditions associated with sodicity. A likely explanation for this discrepancy is that the placement of the ^{32}P isotope in five locations in the current experiment, limited the rate at which it was taken up in the sodic soils. Unlabelled native P is distributed evenly throughout the soil. Increases in P availability with increasing soil sodicity (Table 3-5) and the relatively high P fertility of these soils (42 mg/kg) mitigated the effect of any decrease in root growth and/or function with increasing soil sodicity on plant P concentrations. In contrast, the placement of the labelled P in small isolated volumes in the soil meant that any limitations to root growth and/or function significantly affected its accumulation. This result is of greater importance for soils with lower P fertility than that used in this experiment. In soils of low P fertility, cotton plants may not be able to compensate for reduced root growth by accumulating more P from within a smaller soil area, possibly resulting in declining cotton P concentrations with increasing soil sodicity, even without the occurrence of waterlogging events.

The concentrations and accumulation of ^{32}P measured in the plants of the waterlogging treatments illustrate the effect of sodicity on cotton root activity and/or function following conditions of excess soil moisture (Table 6-4). Increasing soil sodicity reduced the ^{32}P concentrations in the plants exposed to waterlogging in only the 16% ESP treatment but reduced the ^{32}P accumulation in the plants exposed to waterlogging in the 16% and 25% ESP treatments. Together these results illustrate that sodicity also reduces cotton root activity after a waterlogging event.

There was an effect of waterlogging on the labelled P concentrations and accumulation of cotton in all but the most sodic soil. The significant reductions in labelled P concentrations and accumulation that occurred with waterlogging in the soils of low to moderate sodicity illustrate a negative effect of waterlogging on cotton plant function. There was no significant effect of waterlogging on the concentrations or accumulation of labelled P in the plants in the most sodic treatment, which indicates that the physical condition of this soil was sufficiently poor at field capacity that inundation did not further limit root activity and plant function.

6.4.5. *Nutrient concentrations and accumulation*

Sodium

A strong link between increasing sodicity and markedly increased concentrations and accumulation of cotton tissue Na has been well established (Chapters 2, 4 and 5). The majority of the agriculturally significant varieties of cotton are Na-including plants, which means that one of their central mechanisms of tolerance to sodic conditions is to accumulate significant quantities of Na and sequester this nutrient within plant structures (Lauchli and Stelter 1982; Leidi and Saiz 1997). Similarly, the concentrations of Na present in all of the plant tissues sampled increased significantly with increasing soil ESP in the current experiment.

Waterlogging increases plant uptake of Na due to the breakdown of energy dependant Na exclusion mechanisms (Drew and Sisworo 1979). Immediately after the event, waterlogging increased cotton Na concentrations at a moderate sodicity level but not in the non-sodic or two most sodic soils. This result corresponds with those of Drew and Dikumwin (1985), who measured a significant increase in the Na concentrations of corn (*Zea mays* L.) immediately following a waterlogging event, at a solution culture Na concentration of 10.9 mM but not at solution culture Na concentrations of 2.4 and 40 mM. The trend in both this experiment and that outlined by Drew and Dikumwin (1985) was towards increasing plant Na concentrations in the least sodic treatment following exposure to a waterlogging event but this effect was not significant, perhaps due to the relatively low plant Na concentrations measured in both the control and waterlogged soils. Drew and Dikumwin (1985) suggested that no significant differences in corn shoot Na concentrations were apparent between control and waterlogged treatments at the high Na concentration due to the breakdown of the Na exclusion mechanism, even in aerobic conditions. The results of the current experiment support this hypothesis at the initial harvest, but not at the final harvest.

The effect of waterlogging on cotton Na concentrations was magnified with increasing soil sodicity at the final harvest. There was no effect of sodicity on the rate at which the pots returned to field capacity (Table 6-2). It is possible however that the anaerobic conditions (low O_2 and high CO_2 and ethylene) remained longer in soils with higher sodicity levels as a result of poor soil physical conditions reducing gas diffusion. Another possible explanation for this effect is that the plant root damage during the waterlogging event was exacerbated by high soil solution Na concentrations. Further experimentation to determine the nature of the relationship between sodic soil chemistry, waterlogging and Na accumulation is described in Chapter 7.

Increased plant tissue Na limited the vegetative growth of cotton and, when threshold levels (YML Na concentrations >0.18% at harvest) were reached, the reproductive growth of cotton (Chapter 5). The relationship between waterlogging, sodicity and increased Na uptake by cotton is of particular significance to cotton producers, as higher levels of plant tissue Na may lower the threshold soil ESP at which cotton lint yield is reduced. The majority of cotton production systems are based upon furrow irrigation and as such some degree of waterlogging is inevitable during the crop production cycle. There is scope however for reduction in the length and severity of in-crop waterlogging events with improvement in irrigation management practises, such as the use of drip irrigation or precision furrow irrigation.

Cotton plants grown in sodic fields have significantly higher levels of Na in their tissues than those produced under sodic conditions in the glasshouse. Specifically, the plants grown to maturity in soil with an ESP of 24% in the glasshouse experiment described in Chapter 5, accumulated harvest YML Na concentrations of 0.21% (Table 5-4) while the plants grown to maturity in soil with an ESP of 24% in the field experiment described in Chapter 2 accumulated harvest YML Na concentrations of approximately 0.48% (Figure 2-7). The results of this experiment support the hypothesis that an increased frequency and/or severity of waterlogging events in field situations, due to the practise of furrow irrigation contributes to the discrepancies between the results of these two experiments.

Potassium

Soil sodicity reduces the uptake of K by cotton due largely to the adverse physical condition of sodic soils and associated reductions in root growth (Chapter 5). Additionally, anaerobic conditions in plant root environments reduce the uptake of K by plants (Drew and Dikumwin 1985; Drew and Lauchli 1985) and in some situations can result in a net loss of K from the plant root tip (Greenway *et al.* 1992; Wiengweera and Greenway 2004), due to a rapid decline in root ATP levels. Similarly, both the concentrations and total accumulation of K decreased in this experiment with increasing soil sodicity and with exposure of the plants to a period of waterlogging.

Waterlogging decreased the cotton K concentrations at both the initial and final harvests, but this effect was greatest in the 12% ESP treatments. That waterlogging was a significant factor in determining the K status of cotton at this ESP suggests that waterlogging has the potential to exacerbate the K limitations placed upon cotton crops due to the poor soil physical condition of sodic soils. The occurrence of the greatest effect of waterlogging on K concentrations in the moderately sodic soils suggests that the physical condition of the most sodic soil at or near fields capacity, limited cotton K concentrations to a similar extent as an extended period of waterlogging, due to high soil strength and/or poor soil aeration

Phosphorus

Previous glasshouse experiments with this soil established that there was no significant relationship between soil sodicity and cotton P concentrations at or near field capacity but that the total accumulation of P was reduced (Chapter 5). The control treatments in this experiment correspond with these previous results, with no overall relationship between soil sodicity and cotton P concentrations observed, except higher P concentrations measured in the 16% ESP treatment. Plant roots access P largely through the processes of diffusion and direct root interception (Schachtman *et al.* 1998). The P results of these experiments suggest that, at or near field capacity, soil P concentrations were sufficient to provide an adequate supply of P to the plants, despite possible reductions in root growth in sodic soils, due to high soil strength.

In the experiment described in Chapter 2, it was observed that cotton P concentrations and uptake were negatively affected by soil sodicity in a field situation (Figure 2-9) while in the glasshouse experiment described in Chapter 5, no significant relationship between sodicity and cotton P concentrations was measured (Table 5-6). It is suggested that the discrepancy between the glasshouse and field P results may be associated with the occurrence of waterlogging. Less P uptake in sodic field soils could be the result of increased frequency of waterlogging events, as a consequence of the practise of flood irrigation and the poor physical condition of the soil. It is also possible however, that high soil solution Na concentrations exacerbated the effects of waterlogging on cotton P accumulation, by damaging plant tissue.

The duration of the waterlogging event was not prolonged with increasing soil sodicity in this experiment due to the high surface to volume ratio of the pots and the significance of evaporation in the daily water use figure. In field situations however, sodic soils undergo more frequent and/or prolonged waterlogging events than non sodic soils, due to their poor physical condition and associated reductions in hydraulic conductivity (Jayawardane and Chan 1994). Exposure of plant roots to anaerobic conditions results in reduced plant concentrations of P, due to a rapid decline in root ATP levels (McLeod 2001; Trought and Drew 1980a; Wiengweera and Greenway 2004). These results are consistent with the finding that a waterlogging event decreased subsequent cotton P concentration and accumulation across soils with sodicity levels ranging from 2 to 25% in the current experiment. That this effect persisted at the second harvest indicates that the cotton plant is not able to compensate for the reductions in P uptake resulting from the waterlogging event, given a 2-week period at or near field capacity. Thus, it is probable that an increased frequency and/or duration of waterlogging events reduced the P status of cotton grown in sodic soils in the field.

Subjecting cotton plants to a period of waterlogging may also result in a negative interaction between sodicity and cotton P concentrations immediately after the event. The significant negative interaction between sodicity and cotton P concentrations in the waterlogged treatments, at the first harvest contrasts significantly with P concentration results in the control treatment at this time. In the control treatments there was no overall relationship between soil sodicity and cotton P concentrations but the 16% ESP treatment had a higher P concentration than the non-sodic soil. The contrast between the effects of sodicity on cotton P concentrations in the control and waterlogged soils suggests that waterlogging may reduce cotton P concentrations in the presence of high concentrations of Na in the soil solution. Further experimentation to determine the interaction between sodic soil chemistry, waterlogging and cotton nutrition is outlined in Chapter 7. No effect of sodicity on cotton P concentrations was recorded in the plants exposed to waterlogging at the second harvest however, which suggests that soil solution Na did not inhibit the recovery of cotton P uptake from waterlogging and indeed, the plants exposed to the more sodic conditions were able to compensate for any effect of Na on plant P status during the waterlogging event. Because the interaction between sodicity, waterlogging and cotton P concentrations does not persist throughout a two week recovery period, it is unlikely to be as significant as an increased frequency and/or duration of waterlogging events in determining the P status of cotton produced in sodic soils.

6.5. Summary – the effect of waterlogging on the nutrition of cotton in sodic soils

The field experiment in Chapter 2 determined that sodicity produces elevated concentrations and accumulation of Na (Figure 2-7) and reduced concentrations and accumulation of K (Figure 2-8) and P (Figure 2-9) in cotton crops. Waterlogging has the potential to contribute to these patterns of nutrient accumulation. Both the frequency and duration of a waterlogging event can be increased by the adverse physical condition of sodic soils in the field (Jayawardane and Chan 1994) while the adverse chemical condition of sodic soils has the potential to exacerbate the effects of a waterlogging event on plant P and Na status.

In this experiment, the accumulation of labelled P was used to determine the effects of sodicity and waterlogging on cotton plant root function. The most significant effect of sodicity on the recovery of cotton root activity after a waterlogging event occurred in moderately sodic soils, as the adverse physical condition of highly sodic soils also greatly reduced root activity, even at or near field capacity.

Waterlogging increased the concentrations and accumulation of Na in cotton, due to the breakdown of active Na exclusion mechanisms under anaerobic soil conditions. This effect also became more significant with increasing soil sodicity, perhaps due to an extension of the period of anaerobic conditions resulting from the poorer physical condition of the more sodic soils. Alternatively, this could be due to the breakdown of the exclusion mechanism of Na in the cotton roots occurring with the increasingly adverse chemical condition of more sodic soils following a waterlogging event. Further experimentation addressing the interactions between sodic soil chemistry, waterlogging and cotton nutrition is outlined in Chapter 7.

Waterlogging significantly reduced the K status of cotton. This effect was greatest in the moderately sodic soils however, perhaps due to the fact that, in the highly sodic soils, cotton K concentrations were greatly reduced by poor soil physical conditions, even at or near field capacity. The negative effect of waterlogging on the K concentrations of cotton illustrates that an increased incidence and/or severity of waterlogging in sodic soils may exacerbate K nutritional problems in field situations, in conjunction with the direct effects of poor soil physical fertility, outlined in Chapter 5.

Waterlogging was a significant factor in determining the P status of cotton in this experiment across soils ranging in sodicity from 2 to 25% ESP and the plants did not have the ability to compensate for reduced P uptake throughout a waterlogging event, during a two-week period of recovery, despite the relatively high P fertility of the soils used. Immediately after a waterlogging event, there was no significant relationship between sodicity and cotton P concentrations under optimum conditions of soil moisture but in the plants exposed to a waterlogging event, sodicity reduced P concentrations. A possible explanation for this result is that there is an interaction between high levels of soil solution or plant Na and increased damage to the P uptake mechanisms in cotton plants in anaerobic soil environments. Further experimentation to address this issue is outlined in Chapter 7. This effect is not apparent however, after a two-week period of recovery. Thus, an increased frequency/severity of waterlogging events is likely to be more significant than adverse soil chemical conditions in determining the P status of cotton produced in sodic soils.

Chapter 7. Interactions between soil solution chemistry and waterlogging in sodic soils

7.1. Introduction

The dispersive nature of sodic soils can result in low levels of macroporosity and thus reduced soil hydraulic conductivity (Shainberg and Caiserman 1971). Crops produced on sodic soils frequently suffer aeration stress after irrigation or rainfall events (Jayawardane and Chan 1994) as restricted water intake results in waterlogging in the surface soil layers and restricted internal drainage results in waterlogging in sodic subsoils (McIntyre 1979; McIntyre *et al.* 1982).

Plants grown in sodic fields have significantly higher levels of Na and lower levels of P in their tissues (Chapter 2) than those produced under sodic conditions in the glasshouse (Chapter 5). It is likely that an increased incidence and/or duration of waterlogging events in sodic soils contribute to these patterns of nutrient accumulation (Section 6.6). Soil chemical factors also have the potential to contribute to the differential response of cotton plants to potential waterlogging events, according to the sodicity of the soil. It is hypothesized that the rate of recovery of cotton plants from waterlogging may be slower in sodic soils due to increased levels of root damage occurring under conditions of high soil solution Na. Understanding the effects of anoxic soil solution conditions on nutrient uptake and plant growth and its interaction with high levels of soil Na may help to explain poor growth and nutrition of cotton in sodic fields.

When a soil becomes waterlogged, the pore space in the soil structure that usually allows the exchange of gas between the soil and atmosphere is filled with water and diffusion of oxygen is limited. Therefore, waterlogging reduces the O_2 concentrations and increases the CO_2 and ethylene concentrations in the soil (Jackson and Drew 1984). Waterlogging events have been replicated in nutrient culture systems by flushing with N_2 (Drew and Dikumwin 1985; Drew and Lauchli 1985). A limitation of this method is that it removes CO_2 and ethylene from the solution, along with O_2 (Wiengweera *et al.* 1997). Agar dissolved in nutrient solution at a rate of 0.1% (w/w) can be used to prevent convection and thus simulate the slow gas movement that occurs in waterlogged soils. The use of agar mirrors the movement of O_2, CO_2 and ethylene in waterlogged soils and is thus an appropriate method by which to simulate a waterlogging event in a solution culture system (Wiengweera *et al.* 1997). There are some differences between an agar treated solution and a waterlogged soil however, the most significant being the absence of the soil micro-organisms in the nutrient solution. Micro-organisms play an important role in nutrient transformations in waterlogged soils. Additionally, in the agar system anaerobic conditions are only apparent in the rhizosphere, which is not the same as in a waterlogged soil. Thus, although the use of agar-treated nutrient solution more closely reflects a waterlogged soil than flushing with N_2, caution must still be employed when applying the results directly to soil systems.

This chapter concerns a glasshouse experiment growing cotton in nutrient solutions with a range of sodium concentrations (9, 30 and 52 mM), with and without the inclusion of a 7-day period of waterlogging. Labelled ^{32}P was applied to the solutions after waterlogging to assess the effect of sodicity on the rate of recovery of cotton root function. The effect of waterlogging on nutrient accumulation at different levels of soil sodicity was assessed through plant tissue nutrient analysis, both immediately after the event and following a 24 h period of recovery.

7.2. Methods

7.2.1. *Preparation of aerated and anoxic nutrient solutions*

Based on the sodic soil solution compositions outlined in Chapter 4 (Table 4-2), three nutrient solutions were developed, varying in Na concentration (9, 30 and 52 mM). The Na concentrations used reflect those found in the soil solutions of soils with ESP values between approximately 2 and 25%. Basal macronutrients were applied at the following concentrations (mM) Ca 0.9; K 0.3; Mg 1.2, P 0.06; S 0.8. Ammonium and nitrate N were applied at 0.03 mM and 5.3 mM respectively. Basal micronutrients were applied at the following concentrations (μM) – Fe 65; Cu 28; B 83; Zn 11; Mo 0.7. The three nutrient treatments were dissolved in deionised water.

The control treatments were maintained by bubbling air through the nutrient solutions. The nutrient solutions for the waterlogging treatments were created according to the method outlined by Wiengweera *et al.* (1997) by dissolving 0.1% (w/w) agar (Difco Bacto, Difco Laboratories Pty Ltd) in each of the nutrient solutions; heating and stirring was required. Both the aerated and waterlogged nutrient solutions were then autoclaved at 120°C for 15 mins and then cooled with magnetic stirring to prevent the formation of lumps.

7.2.2. *Experimental design*

The experiment was a randomised block design, with cotton grown in 36 jars containing nutrient solutions with three different Na levels. Two aeration regimes were applied during the experiment, including a control treatment that was aerated throughout the experiment and a waterlogging treatment that was treated with agar for a period of 7 days. Two replicates of each sodicity and waterlogging treatment were harvested immediately after the waterlogging event and the remaining four harvested two weeks later

7.2.3. *Plant culture*

This experiment was conducted in a glasshouse at the University of New England, Armidale, NSW Australia. The temperature range of the glasshouse during the experiment was maintained between 20°C and 35°C. Cotton seeds (cv Sicot 289BR, CSD Pty Ltd) were germinated in moist sand in the glasshouse. After 7 days the seedlings were transferred into tubs of solutions containing all of the basal nutrients but no Na. The plants were suspended above the nutrient solutions using a wooden board and plastic cups filled with non-wetting cotton wool.

On the 24th day after germination the plants were transferred to individual foil-wrapped jars filled with 750 mL of treatment solution. The plants were suspended above the solutions using a small hole cut in the jar lid and non-wetting cotton wool. Air was bubbled through each jar using a small pump and plastic tubing. Twelve replicates of each treatment solution were used and the plants grown under aerated conditions for 12 days. The nutrient solutions for all treatments were renewed after 6 days.

The pH values of the nutrient solutions were measured at least daily with a portable pH meter. The pH values of the nutrient solutions were maintained between 6.2 and 6.8 and small fluctuations in pH were corrected as needed by the addition of small quantities of NaOH or HCl and small corrections in the balance of NO_3^- and $NH4^+$ ions in the nutrient solution. The optimum level of NH_4^+ ions needed to stabilise the pH of the solution was found to be approximately 0.8% of total solution N (mM).

On the 37th day after germination, the nutrient solutions of the six replicates of each Na level in the control treatments were renewed and the application of aeration continued. In the six replicates of each Na level in the waterlogging treatments, agar-treated nutrient solutions were applied and aeration removed. The plants were allowed to grow in these solutions for a 7-day period.

7.2.4. *^{32}P Preparation and application*

A 0.74 MBq/mL stock solution of ^{32}P was made by combining 1 mL of 74 MBq ^{32}P and 3.26 g KH_2PO_4 in a total volume of 100 mL of deionised water. A 6.08 mL aliquot of this stock solution was then dissolved into 300 mL of deionised water to produce a 0.015 MBq/mL ^{32}P solution.

Following the 7-day period of waterlogging, two plants from each Na level in the control and waterlogging treatments were harvested. The nutrient solutions of all of the remaining plants were renewed with non-agar treated solutions and aeration was applied to all plants. Labelled P was applied to each replicate immediately following the renewal of the nutrient solution. A total of 0.15 MBq of labelled P was applied to each treatment by adding 10 mL of the isotope solution to each replicate. The uptake of the ^{32}P by the cotton plants was assessed every 90 mins by placing a Geiger counter on the youngest mature leaves (YMLs), with the rest of the plant shielded behind a Perspex screen. The plants were allowed to grow until all replicates were producing Geiger counter readings of >10 counts/s – approximately 24 h.

7.2.5. *Plant harvest and nutrient determination*

The remaining four replicate plants per treatment were removed from the nutrient solution and rinsed in deionised water. The cotton tops were separated from the roots by cutting the plants at the point of emergence of the cotyledons. All plant material was dried in a fan-forced oven at 80^0C, weighed, ground to <2 mm and digested with perchloric acid and hydrogen peroxide, using the sealed chamber method outlined by Anderson and Henderson (1986). The nutrient composition of the samples was determined using the inductively coupled plasma atomic emission spectroscopy (ICPAES). An Australasian Soil and Plant Analysis Council (ASPAC) plant sample was included in the analysis, in order to ensure the accuracy of the digestion process.

In order to determine the ^{32}P concentrations of the samples, 10 mL aliquots of digested cotton tops or roots were placed in 20 mL scintillation vials. The samples were analysed in a Liquid Scintillation Counter (LSC) (United Technologies Packard Tri-carb 2000), by Cerenkov Counting. Counting time was 30 minutes in a channel between 5 and 1700 kev. Radioactivity from ^{32}P was calculated using the counting efficiency (determined from a vial spiked with 1% of the stock solution) and corrected for radioactive decay to establish Bq/g of plant sample.

7.2.6. *Statistical analysis*

The replicates in this experiment were arranged in a randomised block design. A two-way analysis of variance (ANOVA) was used to test the significance of treatment differences ($P<0.05$), with nutrient solution Na concentration and waterlogging as factors, and two replicate plants per treatment at the initial harvest and four plants per treatment at the final harvest. Where significant interactions between the effects of Na and waterlogging were found, differences between individual treatment combinations were further evaluated by least significant difference (LSD) ($P<0.05$) and these values used to inform the labelling of the tables of results with indicators of significance. Statistical analyses were carried out using the Genstat program (7th Edition, Lawes Agricultural Trust) (Payne 1987).

In this analysis, each individual jar of nutrient solution and the associated cotton plant was designated as a replicate, despite the application of the same nutrient solution to each jar in an individual treatment. This approach was valid in this case, as the aim of the experiment was to assess the response of cotton plants to nutrient solution composition and aeration. The most significant within-treatment variation in this system was believed to be derived from genetic variation between individual cotton plants, validating the use of individual plants as treatment replicates.

7.3. Results

7.3.1. *Cotton dry matter accumulation*

Nutrient solution Na concentrations did not have any significant effect on the top (P=0.13) or root dry weight (P=0.87) of cotton at the final harvest (Table 7-1). There was a tendency towards a reduction in cotton top dry weight with higher nutrient solution Na in the control treatment but there was no significant interaction between nutrient solution Na and waterlogging on top (P=0.38) or root dry matter accumulation (P=0.18). Waterlogging decreased both the top and root dry weights of cotton (P<0.001).

Table 7-1 The effect of sodium and waterlogging on the final top and root dry weight of cotton (*Gossypium hirsutum* L.) produced in a nutrient culture system. Values are means of four replicates ± standard errors. ns designates no significant interaction between the effects of sodium and the effects of waterlogging.

Treatment	Na (mM)	Final Top Dry Weight (g)	Final Root Dry Weight (g)
Control	**9**	8.4 ± 0.4	1.8 ± 0.1
	30	8.1 ± 0.5	1.8 ± 0.1
	52	7.0 ± 0.3	1.6 ± 0.1
Waterlogging	**9**	6.0 ± 0.2	1.2 ± 0.1
	30	6.2 ± 0.6	1.2 ± 0.1
	52	5.9 ± 0.2	1.3 ± 0.1
LSD		*ns*	*ns*

7.3.2. *Rate of cotton root recovery from waterlogging*

Waterlogging greatly reduced (P<0.001) cotton root activity, with the plants in the control treatment all generating Geiger counter readings of 2 counts/s within the first 1.5 h after application of the isotope, compared to 2.6 to 4.5 h for plants in the waterlogging treatments (Table 7-2). There was no significant effect of nutrient solution Na on the time taken for the cotton plants to generate Geiger counter readings of 2 (P=0.13) or 10 (P=0.26) counts/s but the interaction between nutrient solution Na level and waterlogging was bordering on being significant at 2 (P=0.08) but not at 10 counts/s (P=0.20). There was no effect of nutrient solution Na on the time taken for the plants in the control treatments to generate Geiger counter readings of 2 counts/s but increasing nutrient solution Na tended to increase the time taken for the plants in the waterlogging treatments to generate Geiger counter readings of 2 counts/s.

The Geiger counter readings increased with time after isotope application in both the control and waterlogging treatments but the plants in the control treatments generated higher Geiger counter readings than those in the waterlogging treatments, both 12 and 24 h after the application of the isotope ($P<0.001$). There was no significant effect of nutrient solution Na on the uptake of labelled P, as measured by the Geiger counter and there was no significant interaction between nutrient solution Na level and waterlogging either 12 or 24 h after the application of the isotope ($P>0.05$).

Table 7-2 The effect of sodium and waterlogging on the accumulation of ^{32}P in the youngest mature leaves of cotton (*Gossypium hirsutum* L.) produced in a nutrient culture system, in the 24 h following a waterlogging event.. Values are means of four replicates ± standard errors. ns designates no significant interaction between the effects of sodium and the effects of waterlogging.

Treatment	Na Level (mM)	Time Taken to Reach a Geiger Counter Reading (h)		Geiger Reading at a Time (counts/s)	
		2 Counts/s	10 Counts/s	12 h	24 h
Control	9	1.5 ± 0.0	3.8 ± 0.8	32.3 ± 8.0	70.5 ± 4.7
	30	1.5 ± 0.0	3.4 ± 0.4	41.8 ± 3.1	74.3 ± 4.3
	52	1.5 ± 0.0	3.5 ± 0.4	44.3 ± 9.2	65.5 ± 6.1
Waterlogging	9	2.6 ± 0.7	15.1 ± 3.5	5.7 ± 1.1	15.1 ± 3.0
	30	4.1 ± 0.9	18.5 ± 3.3	4.2 ± 1.2	13.5 ± 4.4
	52	4.5 ± 0.0	22.1 ± 0.7	4.2 ± 1.0	10.4 ± 2.3
LSD		*ns*	*ns*	*ns*	*ns*

7.3.3.

^{32}P Concentrations and total accumulation

Nutrient solution Na had no significant effect on the top, root or total plant ^{32}P concentrations or accumulation at the final harvest (P>0.05) (Table 7-3). Waterlogging decreased the concentrations and accumulation of labelled P in the cotton tops and total plants averaged over Na levels (P<0.05), but not in the cotton roots (P>0.05). There was no significant interaction between the effects of nutrient solution Na concentration and waterlogging on the top, root or total plant ^{32}P concentrations or accumulation (P>0.05).

Table 7-3 The effect of sodium and waterlogging on the concentrations and accumulation of ^{32}P in cotton (*Gossypium hirsutum* L.) produced in a nutrient culture system. Values are means of four replicates ± standard error. ns designates no significant interaction between the effects of sodium and the effects of waterlogging.

Treatment	Na Level	^{32}P Concentration (Bq/g)			^{32}P Accumulation (kBq)		
	(mM)	Top	Root	Total	Top	Root	Total
Control	**9**	460 ± 120	720 ± 170	500 ± 130	3.8 ± 1.1	1.3 ± 0.3	3.6 ± 0.8
	30	480 ± 160	710 ± 120	510 ± 140	3.9 ± 1.2	1.3 ± 0.3	5.0 ± 1.4
	52	590 ± 180	770 ± 140	640 ± 170	4.1 ± 1.3	1.2 ± 0.2	5.8 ± 1.8
Waterlogging	**9**	70 ± 17	810 ± 50	200 ± 20	0.4 ± 0.1	1.0 ± 0.1	2.0 ± 0.3
	30	110 ± 36	890 ± 160	250 ± 60	0.6 ±0.2	1.1 ± 0.2	2.0 ± 0.5
	52	130 ± 46	880 ± 190	260 ± 60	0.8 ± 0.3	1.2 ± 0.3	2.2 ± 0.6
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

7.3.4. *Nutrient concentrations and accumulation*

Sodium

Cotton top, root and total plant Na concentrations increased with increasing nutrient solution Na concentrations, at both the initial and final harvest (P<0.05) (Table 7-4).

At the initial harvest, there was no significant effect of waterlogging on cotton top, root or total plant Na concentrations and there was no significant interaction between the effects of nutrient solution Na concentrations and waterlogging on cotton top, root or total plant Na concentrations (P>0.05). At the final harvest, waterlogging increased the cotton top Na concentrations (P<0.001). There was however a significant interaction between the effects of nutrient solution Na concentrations and waterlogging on final cotton top Na concentrations (P<0.001), as there was no significant effect of waterlogging on top Na concentrations in the 9 mM Na treatment. Cotton root Na concentrations were not significantly affected by waterlogging at the final harvest (P=0.45) and there was no significant interaction between the effects of nutrient solution Na concentration and waterlogging on final cotton root Na concentrations (P=0.27). Total plant Na concentrations were not significantly affected by waterlogging at the final harvest (P=0.42). There was however a significant interaction between the effects of nutrient solution Na concentration and waterlogging on final total plant Na concentrations (P=0.03), with waterlogging increasing total plant Na concentrations in only the 30 mM Na treatments.

Table 7-4 The effect of sodium and waterlogging on the concentration of sodium in cotton (*Gossypium hirsutum* L.) produced on a nutrient culture system. Initial values are means of two replicates ± standard errors. Final values are means of four replicates ± standard errors. Within columns values with the same letters do not differ significantly (P<0.05) and ns designates no significant interaction between the effects of sodicity and the effects of waterlogging.

Treatment	Na (mM)	Top Na Concentrations (%)		Root Na Concentrations (%)		Total Na Concentrations (%)	
		Initial	Final	Initial	Final	Initial	Final
Control	9	0.41 ± 0.01	0.42 ± 0.01^{a}	0.92 ± 0.32	0.55 ± 0.09	0.56 ± 0.09	0.63 ± 0.15^{ab}
	30	1.23 ± 0.15	0.85 ± 0.05^{b}	1.39 ± 0.37	1.00 ± 0.07	1.27 ± 0.22	0.76 ± 0.76^{b}
	52	2.12 ± 0.28	1.82 ± 0.03^{c}	2.43 ± 0.11	1.31 ± 0.11	2.19 ± 0.17	1.61 ± 0.05^{d}
Waterlogging	9	0.44 ± 0.09	0.43 ± 0.03^{a}	0.70 ± 0.02	0.44 ± 0.02	0.52 ± 0.11	0.42 ± 0.02^{a}
	30	1.27 ± 0.24	1.34 ± 0.03^{c}	1.25 ± 0.04	1.08 ± 0.05	1.25 ± 0.15	1.15 ± 0.05^{c}
	52	1.91 ± 0.32	1.95 ± 0.04^{d}	1.54 ± 0.12	1.52 ± 0.15	1.76 ± 0.23	1.64 ± 0.14^{d}
LSD		*ns*	*0.11*	*ns*	*ns*	*ns*	*0.31*

Potassium

At the initial harvest date waterlogging decreased the top ($P<0.001$), root ($P=0.01$) and total K concentrations ($P<0.001$) (Table 7-5). There were however no significant effects of nutrient solution Na concentration on the initial top ($P=0.07$), root ($P=0.49$) or total plant ($P=0.45$) K concentrations. There was a significant interaction between the effects of nutrient solution Na concentration and waterlogging on cotton initial top K concentrations ($P<0.001$) and initial total cotton K concentrations ($P=0.01$). Increasing nutrient solution Na tended to increase cotton top and total K concentrations in the control treatments but to decrease cotton top K and total K concentrations in the waterlogging treatments. There was no significant interaction between the effects of nutrient solution Na concentrations and waterlogging on initial root K concentrations ($P=0.41$).

At the final harvest there was no significant effect of nutrient solution Na concentration on the cotton top ($P=0.51$), root ($P=0.47$) or total ($P=0.68$) K concentrations and there was no significant interaction between the effects of nutrient solution Na concentrations and waterlogging on cotton top ($P=97$), root ($P=0.39$) or total ($P=0.68$) K concentrations. Waterlogging decreased cotton top and total plant K concentrations ($P<0.001$) and increased cotton root K concentrations ($P=0.01$) at the final harvest.

Table 7-5 The effect of sodium and waterlogging on the concentration of potassium in cotton (*Gossypium hirsutum* L.) produced in a nutrient culture system. Initial values are means of two replicates ± standard errors. Final values are means of four replicates ± standard errors. Within columns values with the same letters do not differ significantly (P<0.05) and ns designates no significant interaction between the effects of sodicity and the effects of waterlogging.

Treatment	Na (mM)	Top K Concentrations (%)		Root K Concentrations (%)		Total K Concentrations (%)	
		Initial	Final	Initial	Final	Initial	Final
Control	**9**	2.06 ± 0.02^{b}	2.28 ± 0.20	3.28 ± 0.67	2.95 ± 0.05	2.33 ± 0.16^{b}	2.60 ± 0.19
	30	2.15 ± 0.06^{b}	2.23 ± 0.21	3.56 ± 0.05	3.28 ± 0.24	2.31 ± 0.01^{bc}	2.36 ± 0.17
	52	2.48 ± 0.01^{a}	2.29 ± 0.08	3.95 ± 0.31	3.27 ± 0.13	2.76 ± 0.00^{a}	2.53 ± 0.04
Waterlogging	**9**	1.77 ± 0.04^{c}	1.55 ± 0.09	3.43 ± 0.27	3.53 ± 0.19	2.04 ± 0.01^{cd}	1.84 ± 0.07
	30	1.77 ± 0.01^{c}	1.50 ± 0.12	2.79 ± 0.12	3.47 ± 0.42	2.03 ± 0.04^{d}	1.85 ± 0.09
	52	1.54 ± 0.05^{d}	1.49 ± 0.16	2.75 ± 0.10	3.56 ± 0.24	1.78 ± 0.10^{d}	1.87 ± 0.18
LSD		*0.14*	*ns*	*ns*	*ns*	*0.28*	*ns*

Phosphorus

There was no significant relationship between nutrient solution Na concentration and cotton top, root or total P concentrations at either the first or second harvests (P>0.05) (Table 7-6). There were no interaction between the effects of nutrient solution Na concentration and waterlogging on cotton top, root or total P concentrations at either the initial or final harvests (P>0.05).

At the initial harvest, waterlogging decreased the top and total P concentrations (P<0.001) but had no significant effect on cotton root P concentrations (P=0.56). Waterlogging decreased cotton top P concentrations at the final harvest (P<0.001) but increased cotton root P concentrations (P<0.001). There was no significant effect of waterlogging on the total cotton P concentrations at the final harvest (P=0.11).

Table 7-6 The effect of sodicity and waterlogging on the concentration of phosphorus in cotton (*Gossypium hirsutum* L.) tops and roots produced in a nutrient culture system. Initial values are means of two replicates ± standard errors. Final values are means of four replicates ± standard errors. ns designates no significant interaction between the effects of sodicity and the effects of waterlogging. Stars indicate significant differences between initial and final phosphorus concentrations.

Treatment	Na (mM)	Top P Concentrations (%)		Root P Concentrations (%)		Total P Concentrations (%)	
		Initial	Final	Initial	Final	Initial	Final
Control	9	0.53 ± 0.05	0.48 ± 0.01	0.58 ± 0.04	0.40 ± 0.05	0.54 ± 0.03	0.44 ± 0.02
	30	0.52 ± 0.03	0.46 ± 0.05	0.58 ± 0.06	0.43 ± 0.02	0.55 ± 0.01	0.46 ± 0.02
	52	0.53 ± 0.01	0.49 ± 0.03	0.60 ± 0.03	0.50 ± 0.03	0.55 ± 0.00	0.49 ± 0.02
Waterlogging	9	0.42 ± 0.01	0.33 ± 0.01	0.64 ± 0.02	0.52 ± 0.03	0.49 ± 0.00	0.41 ± 0.02
	30	0.42 ± 0.02	0.33 ± 0.01	0.59 ± 0.01	0.54 ± 0.01	0.47 ± 0.02	0.44 ± 0.01
	52	0.38 ± 0.00	0.36 ± 0.01	0.58 ± 0.00	0.57 ± 0.04	0.45 ± 0.01	0.46 ± 0.01
LSD		*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

7.4. Discussion

7.4.1. *Cotton dry matter accumulation*

This experiment examined the effects of elevated solution Na concentrations on seedling cotton growth under aerobic and anaerobic conditions. There was no significant effect of nutrient solution Na on cotton top or root dry weight. Similar aerobic conditions were applied in the hydroponics experiment outlined in Chapter 4 (Table 4-2) and nutrient solution Na concentrations of 56 mM reduced cotton height and tended to reduce top dry weight (Table 4-3). The earlier stage of plant growth at harvest in the current experiment may explain the greater reductions in cotton growth measured in Chapter 4. A negative effect of sodicity on cotton growth was not measured in soil experiment of Chapter 5 until 8 weeks after planting (Table 5-1).

Exposure to a period of waterlogging reduced the top and root dry weight of cotton. No effect of waterlogging on the top dry weight of cotton was measured in the soil-based experiment outlined in Chapter 6 (Table 6-2). The results of the current experiment are supported in field production situations, as waterlogging has been reported to reduced the top dry matter accumulation of mature cotton plants after irrigation events (Bange *et al.* 2004; Hocking *et al.* 1987; McLeod 2001). The mechanisms behind the discrepancy between the results of these two experiments is unclear, but it is likely to be related to the different growth mediums used

7.4.2. *Rate of cotton root recovery from waterlogging*

The aim of monitoring the ^{32}P uptake of the cotton in the different treatments using a Geiger counter was to determine the recovery time of the cotton from a waterlogging event at different Na levels. Labelling of the nutrient solution with ^{32}P is an appropriate way to measure the recovery of the plant from anaerobic solution conditions, as greater amounts of isotope will be transported to the YMLs of healthy, functioning and actively growing plants.

Waterlogging decreased the functioning of cotton plants, as measured by a Geiger counter, across the range of Na treatments. The negative effects of anaerobic root environments on ion uptake and transport to shoots, due to a reduction in both energy-dependant active ion transport and transpiration-dependant mass flow are well documented (Drew 1988; McLeod 2001; Trought and Drew 1980c). The poor physical condition of sodic soils has the potential to reduce cotton root function in field production systems by increasing the incidence and/or duration of waterlogging events.

Nutrient solution Na had no effect on the rate of cotton root recovery from waterlogging, as measured by the Geiger counter, in the control treatments. This result suggests that sodic soil solution chemistry, at Na levels corresponding to those observed in Grey Vertosols with ESP values up to approximately 25%, does not limit the nutrient accumulation activity of cotton in an aerated root environment. This result contrasts markedly with those outlined in Chapter 6 (Table 6-3), where a negative effect of sodicity on the concentrations and accumulation of labelled P was measured in an aerobic soil-based system. A comparison of the results of these two experiments highlights the significance of sodic soil physical rather than chemical condition in limiting cotton root activity.

Although not significant there was a trend towards a slight increase in the time taken for the cotton YMLs to produce Geiger counter readings of 2 count/s. Waterlogging increases plant uptake of Na due to the breakdown of energy dependant Na exclusion mechanisms (Drew and Sisworo 1979) and this effect is amplified with increases in soil sodicity (Table 6-5). The accumulation of excess plant Na concentrations does not appear to have limited early recovery of the cotton plants from waterlogging in the current experiment however, as immediately after the event, there was no significant effect of waterlogging on cotton top, root or total plant Na concentrations (Table 7-3). The processes involved in the sequestration of Na within plant structures are active however (Apse *et al.* 1999) and it is possible that waterlogging reduced the ability of the cotton plants to carry out these processes, by depleting cellular ATP levels. An inhibition of Na sequestration within cotton cells may result in plant damage in more sodic treatments, which may in turn slightly reduce the rate of recovery of normal plant function after waterlogging.

The initial slight trend towards a reduction in recovery of root function in response to increasing solution Na was transient, as Geiger counter readings 12 and 24 h later indicated no effect (Table 7-2). Hence, while cotton root recovery from waterlogging may be weakly limited by sodic soil solution chemistry immediately after the event, this effect does not continue for more than a few hours and is insignificant in the overall functioning of the plant over a 24 h period. Low levels of soil macroporosity have the potential to increase the frequency and/or duration of waterlogging events in sodic soils and high soil strength can reduce plant root growth in sodic soils. Given the temporary and insignificant nature of the effect of sodic soil solution chemistry on the rate of recovery of cotton activity after a waterlogging event, the poor physical condition of sodic soils would be overwhelmingly more significant in limiting cotton crop performance in a field situation.

7.4.3. ^{32}P *Concentrations and accumulation*

There were no effects of nutrient solution Na concentration on the concentrations or accumulation of ^{32}P measured in the plants of either the control or waterlogging treatments. Indeed, although not significant, there was a trend towards increasing top and root ^{32}P concentrations with increasing nutrient solution Na concentrations. The results obtained in the control treatments are supported by those measured in the nutrient solution experiment outlined in Chapter 4, with a trend towards increasing plant P concentrations with increasing nutrient solution Na:Ca ratio measured after a 5 week period of growth in an aerobic nutrient solution (Table 4-8). Together the results of these experiments illustrate that there is no direct chemical effect of nutrient solution Na, at concentrations corresponding to the nutrient solutions of Grey Vertosols with ESP values of up to approximately 25%, on cotton root nutrient uptake and transport functions under either aerobic or anaerobic conditions. The trend towards increasing plant concentrations of labelled P with increasing nutrient solution Na is consistent with the negative effect that higher solution Ca has on solution phosphate activity (Cramer *et al.* 1986). The ^{32}P results of the current experiment differ significantly from those obtained in the soil-based experiment outlined in Chapter 6, where increasing soil sodicity reduced the concentrations of labelled P in cotton plants in the control and waterlogging treatments (Table 6-4). The contrast between the results of these two experiments highlights the importance of the poor soil physical condition of sodic soils, rather than their chemical characteristics, in limiting the root function of cotton plants.

Waterlogging decreased the concentrations of labelled P accumulated in cotton tops across the range of Na treatments. A similar result was obtained in the experiment outlined in Chapter 6, in a soil culture system (Table 6-7) and together these results highlight the significance of an anaerobic root environment in limiting cotton root nutrient uptake and transport activity. Again, the negative effect of waterlogging on the accumulation of nutrients in plant tops is well documented, as anaerobic root environments inhibits both ion uptake from the soil solution and ion transport to shoots, due to a reduction in energy-dependant active ion transport processes and transpiration-dependant mass flow (Drew 1988, Trought and Drew 1989a).

In contrast to the cotton tops, waterlogging had no significant effect on the ^{32}P concentrations or accumulation in the cotton roots. This result illustrates that transport of labelled P between the roots and shoots of the cotton plants, was reduced by waterlogging. The transport of plant nutrients from the root to the shoot involves the active use of proton efflux pumps (Hanson 1978) and anaerobic conditions thus have the potential to significantly limit this process by reducing the supply of energy to the plant. In a non-sodic soil-based experiment, McLeod (2001) waterlogged cotton plants for a 7 day period and then added ^{32}P to the soil. Although no significant effect of waterlogging on top or root concentrations of labelled P was measured in these plants after a 7 day period, the stems and leaves of the plants tended to have reduced stem and leaf labelled P concentrations in the waterlogging treatments, whereas no trend towards a reduction in root labelled P concentrations was observed. The lack of any significant result in the experiment outlined by McLeod (2001) can perhaps be related to the lower efficiency of isotope recovery generated in a soil versus a nutrient solution system. These results do however generally support those obtained in the current experiment and suggest that there is a differential effect of waterlogging on nutrient uptake and nutrient loading into vessels for translocation in cotton plant exposed to waterlogging.

7.4.4. *Nutrient concentrations and accumulation*

Sodium

A strong link between increased sodicity and high concentrations and accumulation of cotton tissue Na has been well established (Chapters 4, 5 and 6). Similarly, the concentrations of Na present in both the tops and roots of the plants in this experiment, increased with increasing nutrient solution Na concentrations.

At the initial harvest date, there was no significant effect of waterlogging on cotton top Na concentrations At the final harvest date however, the plants exposed to a period of waterlogging had accumulated higher Na concentrations than those in the control treatments. The discrepancy between the initial and final harvest data emphasises the significance of the period after a waterlogging event in the accumulation of excess quantities of Na in cotton plants. In the soil-based experiments outlined in Chapter 6 (Table 6-5) and by McLeod (2001), a greater effect of waterlogging on the accumulation of Na by cotton plants was also measured in the period of recovery, rather than during the event itself.

Waterlogging increases plant uptake of Na due to the breakdown of energy dependant Na exclusion mechanisms (Drew and Sisworo 1979). In this experiment, there was no significant effect of waterlogging on cotton top Na concentrations in the 9 mM Na treatments either immediately after the waterlogging event or at the final harvest date. A similar result was obtained in cotton plants produced in the non-sodic soil of the experiment outlined in Chapter 6 (Table 6-5). Although the concentrations differ, most likely due to the higher tolerance of cotton to sodicity than corn (Abrol and Bhumbla 1979), these results correspond with those outlined by Drew and Dikumwin (1985), who measured a significant increase in the Na concentrations of corn (*Zea mays* L.) immediately following a waterlogging event, at a solution culture Na concentration of 10.9 mM but not at the lower solution culture Na concentrations of 2.4 mM. It is likely that in non-sodic soil and nutrient solution conditions, no significant differences in shoot Na concentrations were apparent between control and waterlogging treatments due to the relatively low Na concentrations, to which the plants were exposed.

In the 32 mM Na treatment, waterlogging increased the final top Na concentrations by 57%, whereas in the 50 mM Na treatment, waterlogging increased the final top Na concentrations by only 7%. Again, although the concentrations are different, the reduced significance of waterlogging in determining the Na status of cotton plants after a waterlogging event in the high Na treatment corresponds with the results obtained by Drew and Dikumwin (1985), who measured a significant increase in the Na concentrations of corn (*Zea mays* L.) immediately following a waterlogging event, at a solution culture Na concentration of 10.9 mM but not at a solution culture Na concentration of 40 mM. Drew and Dikumwin (1985) suggested that no significant differences in corn shoot Na concentrations was apparent between control and waterlogging treatments at the high Na concentration due to the breakdown of the Na exclusion mechanism, even in aerobic conditions. A similar mechanism may be operating in the current experiment. In contrast to the results of the current experiment and that outlined by Drew and Dikumwin (1985), in the soil-based experiment outlined in Chapter 6, the increases in cotton Na concentrations following a waterlogging event were exacerbated by increasing soil sodicity (Table 6-5). It was hypothesized that this result may be due to a combination of soil physical and chemical factors. The results of the current experiment however illustrate that the exacerbation of the effects of waterlogging on cotton Na concentrations is due to poor soil physical condition extending the frequency and/or duration or waterlogging events, rather than soil chemical factors.

Waterlogging had no significant effect on cotton root Na concentrations at either the initial or final harvests. Similarly, McLeod (2001) observed no significant effect of waterlogging on cotton root Na concentrations 7 days after a waterlogging event in a non-sodic soil. Together the results of these experiments illustrate that anaerobic root environments significantly limit the ability of cotton plants to actively exclude Na from cotton tops.

Potassium

Across both the initial and final harvests, waterlogging decreased the top and total K concentrations of cotton. In contrast, cotton root K concentrations were reduced by waterlogging at the initial harvest but increased by waterlogging at the final harvest. The negative effect of an anaerobic root environment on plant top K concentrations is well documented (Drew and Dikumwin 1985; Drew and Lauchli 1985) and in the case of cotton, has been measured in a soil-based experiment, both immediately and after a 7 day-period of recovery (McLeod 2001). McLeod (2001) also observed that cotton root K concentrations were not significantly affected by waterlogging, either immediately following a waterlogging event or after a 7-day period of recovery. Together the results of the current experiment and those outlined by McLeod (2001) suggest that anaerobic root environments significantly limit the ability of cotton plants to actively move K from cotton roots to shoots during the period of recovery from a waterlogging event. The mechanism behind the positive effect of waterlogging on cotton root K concentrations at the final harvest in the current experiment is unclear, but it is possible that the passive movement of nutrients into root tissue following solution transfer and aeration played a role.

The control and waterlogging treatments of this experiment measured the effects of elevated solution Na concentrations on cotton nutrition under aerobic and anaerobic conditions. In the aerated nutrient solution conditions applied in Chapter 4, a positive effect of nutrient solution Na:Ca ratio and a negative effect of nutrient solution EC on the top and total K concentrations of cotton was measured (Table 4-2). The balance of these two effects was observed in the current experiment, under both aerobic and anaerobic conditions at the final harvest, with no significant effect of nutrient solution composition on cotton K concentrations in either the control or waterlogging treatments. At the initial harvest, nutrient solution aeration affected the response of cotton top K concentrations to increasing nutrient solution Na concentrations, with top K concentrations increasing in the control treatments and decreasing in the waterlogging treatments. The trend towards decreasing cotton top K concentrations with increasing nutrient solution Na concentrations in the waterlogging treatments suggests that Na may exacerbate the negative effect of waterlogging on cotton K concentrations immediately after a waterlogging event. This outcome is however only temporary, with no effect being measured after a 24 h period of recovery. In sodic field situations, the potential for the poor physical condition of sodic soils to limit root growth and increase the incidence and/or severity of waterlogging events would be much more significant in determining the K status of cotton than the transient interaction between soil solution chemistry and waterlogging.

Phosphorus

It is well documented that waterlogging reduces the accumulation of P in plants (Trought and Drew 1980c; Wiengweera and Greenway 2004). At both the initial and final harvests, waterlogging reduced cotton top P concentrations. These results are supported in Chapter 6 (Table 6-7), which illustrated that waterlogging reduced cotton top P concentrations both immediately and following a 7-day period of recovery. There was no significant effect of waterlogging on cotton root P concentrations at the initial harvest but at the final harvest waterlogging increased root P concentrations. In a soil-based experiment, McLeod (2001) observed a significant reduction in cotton leaf P concentrations immediately after a waterlogging event but no significant effect in the roots. Similarly Hongjun *et al.* (2005) measured a significant reduction in the leaf P concentrations of perennial pepper weed (*Lepidium latifolum* L.) following a 7-day period of waterlogging but no significant change in root P concentrations. The mechanism behind the positive effect of waterlogging on cotton root P concentrations at the final harvest date in the current experiment is unclear, but it is possible that the passive movement of nutrients into root tissue following solution transfer and aeration played a role. As with the K results in this experiment, the P results suggest that waterlogging reduce cotton P concentrations by affecting the active transport of P from roots to tops during the period of recovery.

Cotton crops produced in sodic soils commonly have reduced concentrations of P in their tissues (Rochester Unpublished; Figure 2-9). Cotton plants produced in the glasshouse in an artificial range of sodic soils however, did not exhibit any decrease in plant tissue P concentrations with increasing soil sodicity (Table 5-5). The results of the current experiment support the results of Chapter 5 in both aerobic and anaerobic environments, with no significant effect of nutrient solution Na on cotton top, root or total plant P concentrations observed in either the control or waterlogging treatments. It was hypothesized that interactions between sodic soil solution chemistry and waterlogging contributed to the patterns of P accumulation in field situations, with high soil solution Na concentrations exacerbating the effects of waterlogging in cotton P concentrations by increasing the time taken for the plants to recover from a waterlogging event (Section 5.5.5). This hypothesis was supported in Chapter 6, as a slight negative interaction between sodicity and cotton P concentrations was measured in cotton plants exposed to waterlogging, immediately after the event (Table 6-7). No significant effect of nutrient solution Na concentration on the P concentrations of cotton was observed in the waterlogging treatments of the current experiment however, illustrating that the chemical characteristics of sodic soils make little or no direct contributions to reductions in the P concentrations of cotton following waterlogging events.

7.5. Summary – the effect of sodic soil solution chemistry on the nutrition of cotton following a waterlogging event

The results of this experiment, in conjunction with the results of the experiment outlined in Chapter 6, demonstrate that waterlogging has the potential to contribute to the patterns of Na, P and K uptake that have been measured in cotton crops produced in sodic field conditions. In both experiments, exposure of cotton plants to a period of waterlogging increased shoot concentrations of Na and decreased shoot concentrations of P and K. It was unclear, upon the conclusion of the experiment outlined in Chapter 6 however, to what extent the contribution of waterlogging to the patterns of nutrient accumulation in sodic soils is due to soil physical factors increasing the frequency and/or duration of waterlogging events.

It was hypothesized that soil chemical factors, namely high soil solution Na concentrations, may increase the time taken for cotton plants to recover from a waterlogging event, due to the accumulation of excess plant concentrations of Na. In turn, it was speculated that sodic soil solution chemistry led to an exacerbation of the negative effects of waterlogging on the K and P concentrations of cotton plants. Although not significant, the results of the current experiment determined that sodic soil solution chemistry slightly increased the time taken for cotton plants to recover their nutrient accumulation functions after a waterlogging event, but this effect is not significant after a 24 h period of recovery. Similarly, sodic soil solution chemistry slightly exacerbated the effects of waterlogging on cotton K nutrition in the highly sodic nutrient solution treatment, but this effect was not measurable after a 24 h period of recovery. There was no significant effect of sodic soil solution chemistry on the effects of waterlogging on the P nutrition of cotton. The mechanism responsible for the interactions between the effects of nutrient solution Na concentrations and waterlogging on cotton root recovery and initial top K concentrations are not clear from the results of the current experiment. It is possible however that waterlogging effects the active Na transport processes involved in Na distribution in plant storage structures.

The results of the current experiment show that any contribution of waterlogging to the overall patterns of nutrient accumulation in cotton crops produced in sodic fields occurs due to soil physical factors, rather than sodic soil solution chemistry. The contributions of sodic soil solution chemistry to the effects of waterlogging on cotton nutrition are slight and transient and thus unlikely to be significant in a field production situation where soil physical factors have the potential to greatly increase the frequency and/or duration of waterlogging in sodic soils.

Chapter 8. Conclusions and future research opportunities

8.1. The application of research outcomes to cotton field production situations

The experiment described in Chapter 2 was designed to determine the relationship between sodicity and the growth and nutrition of cotton in a commercial field production situation (Moreton Plains, Moree, NSW) and to confirm reports of changes in cotton nutrient status associated with sodic soils (Rochester Unpublished). The results of this experiment were used to inform the design of subsequent glasshouse experiments, which determined the dominant soil physical and chemical processes behind the effects of sodicity on cotton growth and nutrition. The implications of the results of the experiments in Chapters 3 to 7 for the interpretation of the field experiment are outlined below.

The responses of cotton crops in individual fields to sodicity will vary according to soil, climatic, management and varietal factors. The use of the results of the glasshouse experiments to explain the observed patterns of cotton growth and nutrition in the field experiment, does however illustrate that confident conclusions regarding causal relationships between soil and plant characteristics in sodic field situations can be drawn when there is an understanding of the processes in sodic soils that limit cotton growth and nutrition.

8.1.1. *The implications of sodicity for cotton growth at Moreton Plains*

In the field experiment in Chapter 2, increasing sodicity from an ESP of 1 to 7% was accompanied by a 24% reduction in top dry weight and a 36% reduction in fruit dry weight but further increases up to an ESP of 27% tended not to further limit cotton growth (Figure 2-4). At ESP values between 27 and 31% there was a further 29% reduction in cotton top dry weight and a further 20% reduction in cotton fruit dry weight.

In the control soils of the glasshouse experiment (Chapter 5), increasing soil sodicity from an ESP of 2 to 13% resulted in a 38% reduction in top dry weight and a 32% reduction in seed cotton dry weight at ESP levels between 2 and 13% (Table 5-2). The initial decrease in cotton growth with sodicity in the field experiment is relatively consistent with the results observed in the glasshouse experiment and as such is likely due largely to soil physical factors, such high soil strength and an increased incidence/severity of waterlogging events. Some discrepancies are apparent between the growth of cotton in the field (Chapter 2) and glasshouse (Chapter 5) experiments due to the influence of factors such as EC and clay mineralogy on the physical condition of soils at a given sodicity level. Sodic soil solution chemistry (i.e. the accumulation of excess quantities of Na and borderline concentrations of micronutrients) were only limiting to cotton growth in the glasshouse experiment in the absence of poor soil physical condition, at ESP values greater than 19% (Table 5-2, PAM treatment).

It is clear that soil physics has a strong influence on the productivity of cotton crops in sodic soils. The relative contributions of high soil strength and soil anoxia to the physical effects of sodic soils on cotton were not however resolved in this thesis. The relative importance of the drier and wetter ends of the soil moisture range in limiting the productivity of cotton crops is likely to vary according to individual soil characteristics and management factors. Additionally, in contrast to waterlogging, the effects of high soil strength could be markedly different in the field, where gaining adequate rooting volume is an issue, to pots in which the volume is restricted for all treatments.

The reductions in cotton dry matter accumulation and fruit production that occurred in the field experiment at the most sodic site (ESP 31%), are consistent with the growth reductions observed at ESP levels greater than 20% in the PAM-amended soils of the glasshouse experiment in Chapter 5. These reductions in cotton growth were attributed to soil chemical factors, including the accumulation of excess Na concentrations and borderline micronutrient concentrations (Section 5.6). Similarly, in the hydroponics experiment, there was a trend towards reductions in plant height and top dry weight of seedling cotton plants at solution Na concentrations greater than 50 mM (Table 4-3). This Na concentration corresponds to the soil solution of a Grey Vertosol with an ESP of greater than approximately 22% (Table 4-2). Thus, it is likely that soil chemical factors, such as the availability of excess concentrations of Na and inadequate concentrations of micronutrients, contributed to reductions in cotton growth in the most sodic site of the field experiment.

Together the results of the field and glasshouse experiments described in this thesis demonstrate that sodicity limits cotton growth in soils of low to moderate sodicity, largely because of soil physical factors, such as high soil strength and poor soil aeration. Further reductions in cotton growth in highly sodic soils are more likely to be caused by soil chemical factors, such as Na toxicity and micronutrient deficiency. The relationship between waterlogging, sodicity and increased Na uptake by cotton is of particular significance to cotton producers, as higher levels of plant tissue Na may lower the threshold soil ESP at which cotton lint yield is reduced as a result of soil sodicity.

8.1.2. *The implications of sodicity for cotton nutrition at Moreton Plains*

Calcium

There was no significant relationship between sodicity and the Ca concentrations of cotton in the field experiment and all the plants measured had YML Ca concentration greater than 1.9%, which is the level where cotton is considered to be suffering from Ca deficiency (Reuter and Robinson 1986).

The Ca results of the field experiment are supported by the results obtained in the glasshouse experiment (Chapter 5), where no Ca deficiency or significant relationship between sodicity or PAM amendment was measured (Table 5-3). Similarly, no Ca deficiencies were measured in the cotton plant produced in the hydroponics experiment outlined in Chapter 4 (Table 4-6).

Nutrient solution Ca concentrations in this experiment were as low as 0.8 mM (Table 4-1), while the minimum soil solution Ca concentration detected in artificially sodified Grey Vertosols was 2.2 mM (Table 2-6).

Together the results of the field and glasshouse experiments in this thesis demonstrate that Ca nutrition is not likely to limit cotton performance in the Grey Vertosols commonly used in field production situations, across sodicity levels up to 31%.

<u>Sodium</u>

A strong link between increasing sodicity and markedly increasing concentrations and accumulation of cotton tissue Na has been well established in this thesis (Chapters 4, 5, 6 and 7). Similarly, the concentrations of Na present in all of the plant tissues of the crop monitored in the field experiment (Chapter 2), increased significantly with increasing soil ESP.

Cotton plants grown in the sodic field sites had significantly higher levels of Na in their tissues than those produced under conditions of similar sodicity in the glasshouse. For example, the plants grown to maturity in soil with an ESP of 24% in the glasshouse experiment (Chapter 5), accumulated harvest YML Na concentrations of 0.21% (Table 5-4) while the plants grown to maturity in soil with an ESP of 24% in the field experiment (Chapter 2) accumulated harvest YML Na concentrations of approximately 0.48% (Figure 2-7). Waterlogging cotton plants exacerbates Na accumulation in moderate to highly sodic soils (Table 6-5). This experiment supports the hypothesis that an increased frequency and/or severity of waterlogging events in field situations, due to the practise of furrow irrigation, contributes to the discrepancies between the Na concentration results of the field and glasshouse-based experiments. The results of the experiment outlined in Chapter 6 illustrate that waterlogging increases cotton Na concentrations in moderately to highly sodic soils. The results of the experiment outlined in Chapter 7 illustrate that high soil solution Na concentrations do not exacerbate the effects of waterlogging on cotton Na concentrations.

Prior to the experiments in this thesis, the YML Na concentration at which sodicity becomes chemically limiting to cotton production has not been established, due to the difficulty in separating high levels of soil solution Na from other factors, including poor soil physical condition and salinity. In the field experiment (Chapter 2), reductions in cotton dry weight accumulation and fruit production, occurred at mid-season YML Na concentrations greater than 0.13%, but soil physical factors would also have significantly contributed to decreasing cotton growth in these soils. The large decreases in cotton growth that occurred at the most sodic field site corresponded to early season YML Na concentrations of approximately 0.3%. In Chapter 5, there was a reduction in cotton lint yield in the PAM-amended soils at an ESP of 24%, indicating that mid-season YML Na concentrations greater than 0.09% and harvest YML Na concentrations greater than 0.18% could significantly limit cotton crop performance, if not confounded by poor soil physical condition.

At low to moderate sodicity levels, high soil strength and poor soil aeration are likely to be more limiting to cotton production than accumulation of excess quantities of Na. In highly sodic soils however, Na toxicity has the potential to reduce the yield of cotton crops. The relationship between waterlogging, sodicity and increased Na uptake by cotton is also of particular significance to cotton producers, as increases in plant tissue Na concentrations following waterlogging events may lower the threshold soil ESP, at which cotton lint yield is reduced as a result of soil sodicity. The majority of cotton production systems are based upon furrow irrigation and as such some degree of waterlogging is inevitable during the crop production cycle. There is scope however for reduction in the length and severity of in-crop waterlogging events with improvement in irrigation management practises, such as the employment of drip irrigation, precision furrow irrigation or raised beds.

Potassium

The response of cotton K concentrations in the field experiment (Chapter 2) to increasing soil sodicity was dependent on the ESP of the soil (Figure 2-8). At low to moderate sodicity levels cotton K concentrations tended to decrease with increasing soil sodicity. At sodicity levels greater than 21% K concentrations tended to remain stable or to slightly increase with increasing soil sodicity.

The nutrient solution experiment in Chapter 4 determined that at nutrient solution Na concentrations <56 mM, the accumulation of K by cotton plants was not adversely affected by sodic soil solution chemistry (Table 4-7). This Na concentration approximately corresponds to the soil solution of a Grey Vertosol with an ESP of 22% (Table 3-2). A similar result was obtained in the PAM-amended soils of the experiment outlined in Chapter 5, with cotton K concentrations tending to remain stable or to slightly increase with sodicity (Table 5-4). In the nutrient solution experiment outlined in Chapter 7, a slight negative effect of 52 mM Na on cotton K concentrations was measured immediately after the exposure of the plants to a waterlogging event, but this effect was not apparent after a 24 h period of recovery (Table 7-5). Together these results suggest that sodic soil solution chemistry is not a dominant causal factor in the limitations to the K nutrition of cotton that occurred in the field experiment described in Chapter 2, over the length of a production season.

The dispersive nature of sodic soils results in soil physical conditions that are restrictive to root growth and prone to waterlogging. Both restricted root growth (Kuchenbuch *et al.* 1986) and waterlogging (Hocking *et al.* 1987) have the potential to reduce the accumulation of K by plants. Even in the absence of flood irrigation events, the poor physical condition of sodic soils significantly limits the ability of cotton plants to access K (Table 5-5). This effect may be due to high soil strength and/or anoxia. Additionally, an increased incidence and/or duration of waterlogging events in sodic fields under flood irrigation can exacerbate problems with cotton K nutrition at moderate sodicity levels (Table 6-6). Therefore high soil strength and waterlogging events are largely responsible for the declines in cotton crop K nutrition that were measured in the field experiment at ESP levels between 1 and 21%.

There was a tendency for the YML and top K concentrations of the cotton crop measured in the field experiment, to remain stable or to slightly increase at the field sites with ESP values of 27 and 31%. The most likely explanation for this pattern of nutrient accumulation is that in these highly sodic sites, the growth of the crop was more greatly limited than its ability to accumulate K, resulting in slight increases in crop K concentrations. This proposal is supported by the fact that the top dry weights of the plants in the site with an ESP of 31% were significantly lower than at any other site and these plants also accumulated the lowest total amount of K in their tops (Table 7-2).

Contrary to long held belief, high soil solution ratios of Na:K (Amtmann and Sanders 1998) and Na:Ca (Cramer *et al.* 1985) play little to no role in K deficiency in cotton crops produced in sodic field situations. The known selectivity of root uptake channels for K is not significantly interfered with by concentrations of Na found even in highly sodic (< 25%) soils, with high soil solution Na concentrations actually tending to increase cotton K top concentrations in the absence of an adverse soil physical environment (Table 4-7). Together the results of the glasshouse and field experiments described in this thesis suggest that the high soil strength and poor aeration of sodic soils have the potential to limit the K nutrition of cotton. Potassium deficiency, in turn, may limit crop productivity at low to moderate ESP levels. Sodic soil solution chemistry does not significantly limit the K nutrition of a cotton crop over the length of a production season, despite the large ratios of Na: K that exist in sodic soil solutions. In highly sodic soils, factors other than cotton K nutrition, including accumulation of excess plant concentrations of Na and micronutrient deficiencies, become more limiting to cotton growth than K nutrition. This, in turn, may result in increases in cotton crop K concentrations with increasing soil sodicity, at high ESP levels.

Phosphorus

The response of cotton P concentrations in the field experiment (Chapter 2) to increasing soil sodicity was dependent on the ESP of the soil (Figure 2-9). At low-moderate sodicity levels cotton P concentrations tended to decrease with increasing soil sodicity. At sodicity levels greater than 21% cotton YML P concentrations decreased but top and root P concentrations tended to increase with increasing soil sodicity. It is important to note however, that the YML P concentrations of this crop remained above 0.28%, which is the concentration where P deficiency occurs (Reuter and Robinson 1986). This result suggests that K nutrition was more limiting to the performance of this cotton crop than P nutrition.

In the nutrient solution experiment outlined in Chapter 4, there was a trend towards little change or a slight increase in cotton P concentrations with increasing nutrient solution Na: Ca ratio. This result suggests that nutrient solution Na does not significantly limit the accumulation of P by cotton. In the soil-based glasshouse experiment outlined in Chapter 5, the P concentrations of the soil solutions rose significantly with increasing soil sodicity (Table 3-5) due to the dissolution of Ca-P compounds and the release of sorbed P with increasing clay surface negative potential (Curtin *et al.* 1992a; Gupta *et al.* 1990). Hence, sodic soil chemistry suggests better P nutrition of cotton through greater availability of soil P. The PAM treatments of this experiment support this proposal, with no effect of sodicity on the YML or shoot P concentrations and the P concentrations of the roots tending to increase with increasing soil sodicity (Table 5-5). Similarly, in the nutrient solution experiment outlined in Chapter 7, no significant effect of nutrient solution Na on cotton P concentrations was measured in either aerated or anaerobic root environments (Table 7-6). Together these results suggest that sodic soil solution chemistry is not directly responsible for the limitations to the P nutrition of cotton that occurred in the field experiment described in Chapter 2.

The dispersive nature of sodic soils results in soil physical conditions that are restrictive to root growth and prone to waterlogging. Both restricted root growth (Cornish *et al.* 1984) and waterlogging (Hocking *et al.* 1987) have the potential to reduce the accumulation of P by plants. No relationship between soil sodicity the P concentrations of cotton was measured in the glasshouse experiment (Chapter 5), under conditions of careful soil moisture management

(Table 5-5). A significant factor contributing to the discrepancy between the P results of the field experiment (Chapter 2) and the glasshouse experiment (Chapter 5) were the P concentration of the soils; the soils used in the glasshouse experiment had uniformly high P fertility (42 mg/kg; Appendix 1) and the soils in the field that produced plants with the lowest P concentrations had soil P concentrations bordering on the critical concentration of 6 mg/kg (Dorahy *et al.* 2002) (Table 2-1). Waterlogging did however limit cotton P concentrations across a range of soil sodicity levels in the glasshouse experiment described in Chapter 6 (Table 6-7). Given these results, it is likely that the lack of flood irrigation and waterlogging events in the glasshouse situation contributed to the discrepancy between the P concentration results of the field (Chapter 2) and glasshouse (Chapter 5). An increase in the frequency and/or severity of waterlogging events with increasing soil sodicity is likely to have contributed to the declines in P nutrition that were measured in the cotton crop described in Chapter 2 at ESP levels up to 21%.

The contrast between the P results of the experiments outlined in Chapters 2 and 5, highlights the importance of adequate soil P concentrations in maintaining cotton P nutrition. The P status of soils has commonly been found to decrease with increasing soil sodicity (Naidu *et al.* 1996; Rochester Unpublished), despite the increased availability of P in sodic soils observed by Curtin *et al.* (Curtin *et al.* 1992b) and Gupta *et al.* (1990). The nature of the relationship between sodicity and decreasing soil P status in field soils remains undetermined, but it is likely that the frequent occurrence of waterlogging in sodic soils contributes to this relationship. Phosphorus availability in Vertosols is driven by sorption processes with the Fe and Al oxide surfaces of the soil (Dorahy *et al.* 2002). The decrease in bicarbonate extractable P measured in this soil with increasing sodicity is most likely associated with occlusion of P as a result of waterlogging and oxide dissolution and reprecipitation during prolonged wetting and drying cycles. This issue has been highlighted in flooded rice production (Willett 1982). It is also possible however that the reductions in crop P uptake occurring in sodic soils as a result of their poor physical and chemical fertility (Figure 2-9), in turn results in lower P return in litter and a smaller amount of labile P in the soil. The decreasing P status of soils with increasing soil sodicity has ramifications for the P nutritional status of cotton crops.

In the most highly sodic sites of the field experiment described in Chapter 2, the P status of the crop improved, with the top P concentrations of the plants in the most sodic site being approximately equal to the P concentrations of those in the least sodic site. A number of factors may have contributed to this rising pattern of crop P concentrations. Firstly, in the sites with ESP values between 21 and 31%, the growth of the crop may have been more limited than its ability to accumulate P, resulting in rising crop P concentrations. The amount of P accumulated in the cotton tops did not decline significantly at ESP values greater than 7% however, suggesting that this factor was not solely responsible (Table 7-6). Secondly, the P concentration of the soil increased from 9.9 mg/kg in the top 30 cm of the soil profile at an ESP of 21% to 20 mg/kg in the top 30 cm of the soil profile at an ESP of 31% (Table 7-1), which may also have contributed to the improved P status of the crop with in the highly sodic soils. An increased incidence/severity of waterlogging events in sodic soils has been implicated in decreasing cotton P concentrations in sodic soils (Table 6-7). Thus, it is also possible that the highly sodic nature of the surfaces of these soils resulted in a failure or irrigation water to infiltrate and thus a lower frequency of waterlogging events and an improved crop P status.

Together the results of the glasshouse and field experiments described in this thesis suggest that the poor physical condition of sodic soils has the potential to limit the P nutrition of cotton, by increasing the incidence and/or severity of waterlogging events. In addition, the P status of soils has commonly been found to decrease with increasing soil sodicity (Naidu *et al.* 1996; Rochester Unpublished), possibly due to occlusion of P during prolonged wetting and drying cycles and reductions in organic matter returns to the soil. This is also a significant factor in determining the P status of cotton crops produced in sodic soils.

8.1.3. *Summary – the application of research outcomes to field production situations*

The effect of soil sodicity on the productivity of a cotton crop is determined by a variety of soil, crop management and climatic factors. It is therefore impossible for cotton producers to directly apply the results of this thesis to their individual fields. The value of the research outcomes of this thesis lie in their potential to improve the understanding of the soil processes that limit cotton productivity in sodic soils. In this Chapter the results of the glasshouse experiments (Chapters 4-7) have been used in the interpretation of the results of the field experiment (Chapter 2). This process has illustrated the potential for detailed soil and plant measurements from a cotton field to be combined with an understanding of the soil processes that limit cotton production in sodic systems. In this way it is possible to draw confident conclusions regarding causal relationships between soil properties and crop growth and nutritional outcomes in a variety of sodic field situations. An understanding of the soil processes responsible for limitations to cotton crop growth and nutrition in sodic soils is also important, as it will allow cotton producers to apply targeted management strategies to problem sodic soils.

8.2. Future research opportunities

The experiments described in this thesis have determined the dominant soil processes that limit the growth and nutrition of cotton crops in sodic soils. Further experimentation is now required to determine the effectiveness of a variety of crop management practises in reducing the impacts of these soil processes on cotton growth and nutrition.

This thesis has highlighted the potential for high soil strength in dry soil conditions and poor soil aeration in wet soil conditions, to limiting the growth and nutrition of cotton crops produced in sodic soils. Further research needs to be carried out to determine the relative contributions of high soil strength and waterlogging to the physical effects of sodic soils on cotton. This type of research is necessary to allow irrigators to manage their soil moisture contents within the appropriate range of soil moisture contents. Further research, addressing both the most appropriate management of furrow irrigation and the application of new irrigation techniques (sprinkler and drip) to sodic soils would also be a beneficial addition to the work completed during this project.

This thesis has also highlighted the potential for restricted root growth to result in nutrient deficiency (especially K deficiency), in cotton crops produced in sodic soils. This outcome suggests that fertiliser application may play an important role in improving the nutrition of cotton in sodic soils. Further research, addressing the potential for various fertiliser application techniques (placement, timing and forms) to reduce nutritional problems in sodic soils would be another beneficial addition to the work completed during this project.

At low to moderate sodicity levels, improving the physical fertility of sodic soils holds the key to improving the growth and nutrition of cotton crops. Further research, addressing the effects and economic benefits of soil conditioning agents such as gypsum and PAM on cotton growth and nutrition in soils of low to moderate sodicity would be a beneficial addition to this thesis. Similarly, the potential for green manure crops to improve the physical condition of sodic soils by increasing soil organic matter levels needs to be further addressed.

References

Abrol IP, Bhumbla DK (1979) Crop response to differential gypsum applications in a highly sodic soil and the tolerance of several crops to exchangeable sodium under field conditions. *Soil Science* **127**, 79-85.

Al-Ani TA, Ouda NA (1972) Distribution of cations in bean plants grown at varying K and Na levels. *Plant and Soil* **37**, 641-648.

Allison LE (1956) Soil and plant responses to VAMA and HPAN soil conditioners in the presence of high exchangeable sodium. *Soil Science Society of America Proceedings* **20**, 147-151.

Amtmann A, Sanders D (1998) Mechanisms of Na^- uptake by plant cells. *Advances in Botanical Research* **29**, 75-112.

Anderson DL, Henderson LJ (1986) Sealed chamber digest for plant nutrient analysis. *Agronomy Journal* **78**, 937-938.

Apse MP, Aharon GS, Snedden WA, Blumwald E (1999) Salt tolerance conferred by overexpression of a vacuolar Na^+/H^+ antiport in Arabidopsis. *Science* **285**, 1256-1258.

Ashraf M, Ahmad S (2000) Influence of sodium chloride on ion accumulation, yield components and fibre characteristics in salt-tolerant and salt-sensitive lines of cotton (*Gossypium hirsutum* L.). *Field Crops Research* **66**, 115-127.

Aslam M, Muhammad N, Qureshi RH, Ahmad Z, Nawaz S, Akhtar J (2003) Calcium and salt-tolerance of rice. *Communications in Soil Science and Plant Analysis* **34**, 3013-3031.

Atwell BJ (1988) Physiological responses of lupin roots to soil compaction. *Plant and Soil* **111**, 277-281.

Ayars JE, Hutmacher RB, Schoneman RA, Vail SS, Pflaun T (1994) Long term use of saline water for irrigation. *Irrigation Science* **14**, 27-34.

Bains SS, Fireman M (1964) Effect of exchangeable sodium percentage on the growth and absorption of essential nutrients and sodium by five crop plants. *Agronomy Journal* **56**, 432-435.

Baker DN, Hesketh JD (1969) Respiration and the balance in cotton (*Gossypium hirsutum* L). In 'Beltwide Cotton Production Research Conferences.' New Orleans, January 7-8. pp. 60-64. (National Cotton Council, Memphis.).

Bange MP, Milroy SP, Thongbai P (2004) Growth and yield of cotton in response to waterlogging. *Field Crop Research* **88**, 129-142.

Barzegar AR, Nelson PN, Oades JM, Rengasamy P (1997) Organic matter, sodicity and clay type: influence on soil aggregation. *Soil Science Society of America Journal* **61**, 1131-1137.

Barzegar AR, Oades JM, Rengasamy P, Giles L (1994) Effect of sodicity and salinity on the disintegration and tensile strength of an Alfisol under different cropping systems. *Soil and Tillage Research* **32**, 329-345.

Ben-Hayyim G, Kafkafi U, Gahmore-Newman R (1987) The role of internal potassium in maintaining growth of cultured *Citrus* cells on increasing NaCl and $CaCl_2$ concentrations. *Plant Physiology* **83**, 434-439.

Bernstein L, Pearson GA (1956) Influence of exchangeable sodium on the yield and chemical composition of plants 1. *Soil Science* **82**, 247-258.

Blair LM, Taylor GJ (2004) Maintaining exponential growth, solution conductivity and solution pH in low ionic strength solution culture using a computer-controlled nutrient delivery system. *Journal of Experimental Botany* **55**, 1557-1567.

Boursier PJ, Lauchli A (1990) Growth responses and mineral relations of salt-stressed sorghum. *Crop Science* **30**, 1226-1233.

Box S, Schachtman DP (2000) The effect of low concentrations of sodium on potassium uptake and growth of wheat. *Australian Journal of Plant Physiology* **27**, 175-182.

Bradford JM, Ferris JE, Remley PA (1987) Interrill soil erosion processes: I. Effect of surface sealing on infiltration, runoff and soil splash detachment. *Soil Science Society of America Journal* **51**, 1566-1571.

Carr CE, Greenland DJ (1975) Potential application of polyvinyl acetate and polyvinyl alcohol in the structural improvement of sodic soils. *Soil Science Society of America Journal* **7**, 47-63.

Carter MR, Webster GR (1990) Use of the calcium-to-total-cation ratio in soil saturation extracts as an index of plant-available calcium. *Soil Science* **149**, 212-217.

Carter MR, Webster GR, Cairns RR (1979) Calcium deficiency in some solonetzic soils of Alberta. *Journal of Soil Science* **30**, 161-174.

Cartwright B, Zarcinas BA, Spouncer LR (1986) Boron toxicity in South Australian barley crops. *Australian Journal of Agricultural Research* **37**, 351-359.

Chang CW, Dregne HE (1955) Effect of exchangeable sodium on soil properties and on growth and cation content of alfalfa and cotton. *Soil Science Society of America Proceedings* **19**, 29-35.

Chassot A, Richner W (2002) Root characteristics and phosphorus uptake of maize seedlings in a bilayered soil. *Agronomy Journal* **94**, 118-127.

Chartres CJ (1993) Sodic soils: an introduction to their formation and distribution in Australia. *Australian Journal of Soil Research* **31**, 751-760.

Chen Y, Barak P (1982) Iron nutrition of plants in calcareous soils. *Advances in Agronomy* **35**, 217-240.

Churchman GJ, Skjemstad JO, Oades JM (1993) Influence of clay minerals and organic matter on effects of sodicity on soils. *Australian Journal of Soil Research* **31**, 779-800.

Clark LJ, Whalley WR, Barraclough PB (2003) How do roots penetrate strong soil? *Plant and Soil* **255**, 93-104.

Colwell JD (1966) The estimation of the phosphorus fertiliser requirements of wheat in southern NSW by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry* **3**, 190-197.

Constable GA, Bange MP (2006) What is cotton's sustainable yield potential. *The Australian Cottongrower* **26**, 8-11.

Cook GD, So HB, Dalal RC (1992) Structural degradation of two Vertosols under continuous cultivation. *Soil and Tillage Research* **24**, 47-64.

Cornish PS, So HB, McWilliam JR (1984) Effects of soil bulk density and water regime on root growth and uptake of phosphorus by ryegrass. *Australian Journal of Experimental Agriculture* **35**, 631-644.

Cramer GR (1992) Kinetics of maize leaf elongation. 2. Responses of a Na-excluding cultivar and a Na-including cultivar to varying Na/Ca salinities. *Journal of Experimental Botany* **43**, 857-864.

Cramer GR, Epstein E, Lauchli A (1989) Na-Ca interactions in barley seedlings: relationship to ion transport and growth. *Plant, Cell and Environment* **12**, 551-558.

Cramer GR, Lauchli A (1986) Ion activities in solution in relation to Na^+ and Ca^{2+} interactions at the plasmalemma. *Journal of Experimental Botany* **17**, 321-330.

Cramer GR, Lauchli A, Epstein E (1986) Effects of NaCl and $CaCl_2$ on ion activities in complex nutrient solutions and root growth of cotton. *Plant Physiology* **81**, 792-797.

Cramer GR, Lauchli A, Polito VS (1985) Displacement of Ca^{2+} by Na^{+} from the plasmalemma of root cells. *Plant Physiology* **79**, 207-211.

Cramer GR, Lynch J, Lauchli A, Epstein E (1987) Influx of Na^{+}, K^{+} and Ca^{2+} into roots of salt-stressed cotton seedlings. *Plant Physiology* **83**, 510-516.

Croser C, Bengough AG, Pritchard J (2000) The effect of mechanical impedance on root growth in pea (*Pisum sativum*).2. Cell expansion and wall rheology during recovery. *Physiologia Plantarum* **109**, 150-159.

Cruz-Romero G, Coleman NT (1975) Reactions responsible for high pH of Na-saturated soils and clays. *Soil Science* **26**, 169-175.

Curtin D, Naidu R (1998) Fertility constraints to plant production. In 'Sodic Soils: Distribution, Properties, Management and Environmental Consequences'. (Eds ME Sumner, R Naidu) pp. 107-123. (Oxford University Press: Oxford).

Curtin D, Selles F, Steppuhn H (1992a) Influence of salt concentration and sodicity on the solubility of phosphate in soils. *Soil Science* **153**, 409-416.

Curtin D, Steppuhn H, Selles F (1994) Effects of magnesium on cation selectivity and structural stability of sodic soils. *Soil Science Society of America Journal* **58**, 730-737.

Curtin D, Syers JK, Bolan NS (1992b) Phosphate sorption by soil in relation to exchangeable cation composition and pH. *Australian Journal of Soil Research* **31**, 137-149.

da Silva AP, Kay BD (1987) Estimating the least limiting water range of soils from properties and management. *Soil Science Society of America Journal* **61**, 877-883.

da Silva AP, Kay BD, Perfect E (1994) Characteristics of the least limiting water range of soils. *Soil Science Society of America Journal* **58**, 1775-1781.

Dang Y, Dalal R, Harms B, Routley R, Kelly R, McDonald M (2004) Subsoil constraints in the grain cropping soils of Queensland. In 'Supersoil 2004: Proceedings of the 3rd Australian New Zealand Soils Conference'. Sydney. (Ed. B Singh). (The Regional Institute Ltd).

Debnath NC, Datta NP (1974) Influence of exchangeable sodium on the utilization of applied phosphorus and nonexchangeable potassium by the plant. *Indian Agriculturalist* **18**, 31-35.

Dontsova KM, Norton LD (2002) Clay dispersion, infiltration and erosion as influenced by exchangeable calcium and magnesium. *Soil Science* **167**, 184-193.

Dorahy C, Rochester IJ, Blair GJ (2002) Response of field grown cotton (*Gossypium hirsutum* L.) to phosphorus fertilisation in alkaline soils eastern Australia. *Australian Journal of Soil Research* **42**, 913-920.

Drew MC (1988) Plant injury and adaptation to oxygen deficiency in the root environment: A review. *Plant and Soil* **75**, 179-199.

Drew MC, Dikumwin E (1985) Sodium exclusion from the shoots by roots of *Zea mays* (cultivar LG 11) and its breakdown with oxygen deficiency. *Journal of Experimental Botany* **36**, 55-62.

Drew MC, Lauchli A (1985) Oxygen-dependent exclusion of sodium ions from shoots by roots of *Zea mays* (cv Pioneer 3906) in relation to salinity damage. *Plant Physiology* **79**, 171-176.

Drew MC, Sisworo EJ (1979) The development of waterlogging damage in young barley plants in relation to plant nutrient status and changes in soil properties. *New Phytologist* **82**, 310-314.

Eissenstat DM (1992) Costs and benefits of constructing roots of small diameter. *Journal of Plant Nutrition* **15**, 763-782.

Emerson WW, Chi CL (1977) Exchangeable calcium, magnesium and sodium and the dispersion of illites in water. 2. Dispersion of illites in water. *Australian Journal of Soil Research* **15**, 255-262.

Epstein E (1961) The essential role of calcium in selective cation transport by plant cells. *Plant Physiology* **36**, 437-444.

Epstein E (1966) Dual pattern of ion absorption by plant cells and by plants. *Nature* **212**, 1324-1327.

Falatah AM (1998) Phosphate extractability and mobility in leached soil columns as affected by polymer amendments. *Arid Soil Research and Rehabilitation* **12**, 335-343.

Filep G (1999) 'Soil Chemistry: Processes and Constituents.' (Akademiai Kiado: Budapest).

Gardiner EA, Shaw RJ, Smith GD, Coughlan KJ (1984) Plant available water capacity: Concepts, measurement and prediction. In 'Properties and Utilization of Cracking Clay Soils'. (Eds JW McGarity, EH Hoult, HB So) pp. 164-175. (University of New England: Armidale).

Gardner EA, Shaw RJ, Smith GD, Coughlan KJ (1984) Plant available water capacity: Concepts, measurement and prediction. In 'Properties and Utilization of Cracking Clay Soils'. (Eds JW McGarity, EH Hoult, HB So) pp. 164-175. (University of New England: Armidale).

Gorham J, Young EM (1996) Wild relatives of cotton and rice as sources of stress resistance traits. In 'Eurapia Meeting on Tropical Plants'. Montpellier. (CIRAD).

Grattan SR, Grieve CM (1992) Mineral element acquisition and growth response of plants in saline environments. *Agriculture, Ecosystems and Environment* **38**, 275-300.

Greenway H, Waters I, Newsome J (1992) Effects of anoxia on uptake and loss of solutes in roots of wheat. *Australian Journal of Plant Physiology* **19**, 233-247.

Guerrero-Alves J, Pla-Sentis I, Carnacho R (2002) A model to explain high values of pH in alkali sodic soil. *Scientia Agricola* **59**, 763-770.

Gupta RK, Singh RR, Tanji KK (1990) Phosphorus release in sodium dominated soils. *Soil Science Society of America Journal* **54**, 1254-1260.

Hanson JB (1978) Application of the chemi-osmotic hypothesis to ion transport across the root. *Plant Physiology* **62**, 402-405.

Hanson JB (1984) The function of calcium in plant nutrition. In 'Advances in Plant Nutrition'. (Eds PB Tinker, A Lauchli) pp. 149-208. (Praeger: New York).

Hillel D (1980) 'Fundamentals of Soil Physics.' (Academic Press: New York).

Hingston FJ (1964) Reactions between boron and clays. *Australian Journal of Soil Research* **2**, 83-95.

Hocking PJ, Reicosky DC, Meyer WS (1985) Nitrogen status of cotton subjected to two short-term periods of waterlogging of varying severity using sloping plot water-table facility. *Plant and Soil* **87**, 375-391.

Hocking PJ, Reicosky DC, Meyer WS (1987) Effects of intermittent waterlogging on the mineral nutrition of cotton. *Plant and Soil* **101**, 211-221.

Hodgson AS (1982) The effects of duration, timing and chemical amelioration of short-term waterlogging in a cracking grey clay. *Australian Journal of Agricultural Research* **33**, 1019-1028.

Hodgson AS, Constable GA, Duddy GR, Daniells LG (1990) A comparison of drip and furrow irrigated cotton on a cracking clay soil. *Irrigation Science* **11**, 143-148.

Hodgson AS, Lindsay WL, Trierweiler JF (1966) Micronutrient cation complexing in soil solution: 2. Complexing of zinc and copper in displaced solution from calcareous soils. *Soil Science Society of America Proceedings* **30**, 723-726.

Holloway RE, Alston AM (1992) The effects of salt and boron on growth of wheat. *Australian Journal of Agricultural Research* **43**, 987-1001.

Hongjun C, Qualls RG, Blank RR (2005) Effect of flooding on photosynthesis, carbohydrate partitioning and nutrient uptake in the invasive exotic *Lepidium latifolium*. *Aquatic Botany* **82**, 250-268.

Huang J, Redmann RE (1995) Responses of growth, morphology and anatomy to salinity and calcium supply in cultivated and wild barley. *Canadian Journal of Botany* **73**, 1859-1866.

Hubble GD (1984) The cracking clay soils: definition, nature, genesis and use. In 'The Properties and Utilization of Cracking Clay Soils'. (Eds JW McGarity, EH Hoult, HB So) pp. 3-13. (University of New Enland: Arnidale).

Hulme PJ (1987) An evaluation of seedbed preparation methods for growing irrigated cotton in grey clays. Doctor of Philosophy, University of New England.

Hulugalle NR, Entwistle P (1997) Soil properties, nutrient uptake and crop growth in an irrigated Vertosol after nine years of minimum tillage. *Soil and Tillage Research* **42**, 15-32.

Hulugalle NR, Entwistle P, Scott F, Kahl J (2001) Rotation crops for irrigated cotton in a medium-fine self-mulching grey Vertosol. *Australian Journal of Soil Research* **39**, 317-328.

Hulugalle NR, Finlay LA (2003) EC [sub1:5]/exchangeable Na, a sodicity index for cotton farming systems in irrigated and rain-fed Vertosols. *Australian Journal of Soil Research* **41**, 761-770.

ICAC (2005) Cotton World Statistics: Bulletin of the International Cotton Advisory Committee. International Cotton Advisory Committee, Washington.

Ingles OG (1968) Advances in soil stabilization, 1961-67. *Review of Pure and Applied Chemistry* **18**, 291-310.

Isbell RF (1996) 'The Australian Soils Classification.' (CSIRO Publishing: Collingwood, Victoria).

Jackson MB, Drew MC (1984) Effect of flooding on growth and metabolism of herbaceous plants. In 'Flooding and Plant Growth'. (Ed. TT Kozlowski) pp. 47-128. (Academic Press: London).

Jayawardane NS, Blackwell J, Muirhead WA (1987) Research strategies in planning and evaluating soil ameliorative techniques on clay soils. In 'Effects of management practices on soil physical properties'. Toowoomba. (Eds KJ Coughlan, PN Troung) pp. 213-217. (Queensland Department of Primary Industries).

Jayawardane NS, Chan KY (1994) The management of soil physical properties limiting crop production in Australian sodic soils: a review. *Australian Journal of Soil Research* **32**, 13-44.

Johnson CK, Eskridge KM, Wienhold BJ, Doran JW, Peterson GA, Buchleiter GW (2003) Using electrical conductivity classification and within field variability to design field scale research. *Agronomy Journal* **95**, 602-613.

Joshi YC, Qadar A, Bal AR, Rana RS (1980) Sodium/potassium index of wheat seedlings in relation to sodicity tolerance. In 'International Symposium on Salt-Affected Soils: Principles and Practises for Reclamation and Management'. Karnal, India pp. 457-460. (Central Soil Salinity Research Institute).

Kazman Z, Shainberg I, Gal M (1983) Effect of low levels of exchangeable Na and applied phosphogypsum on the infiltration rate of various soils. *Soil Science* **35**, 184-192.

Kent IM, Lauchli A (1985) Germination and seedling growth of cotton: salinity-calcium interactions. *Plant, Cell and Environment* **8**, 155-159.

Keren R, Gast RG (1981) Effects of wetting and drying cycles and of exchangeable cations on boron adsorption by Na montmorillonite. *Soil Science Society of America Journal* **45**, 45-48.

Kinraide TB (1998) Three mechanisms for the calcium alleviation of mineral toxicities. *Plant Physiology* **118**, 513-520.

Kinraide TB (1999) Interactions among Ca^{2+}, Na^{+} and K^{+} in salinity toxicity: quantitative resolution of multiple toxic and ameliorative effects. *Journal of Experimental Botany* **50**, 1495-1505.

Kopittke PM, Menzies NW (2005a) Effect of pH on Na induced Ca deficiency. *Plant and Soil* **269**, 119-129.

Kopittke PM, Menzies NW (2005b) Mg induced Ca deficiency under alkaline conditions. *Plant and Soil* **269**, 245-250.

Kopittke PM, So HB, Menzies NW (2005) Effect of ionic strength and clay mineralogy on Na-Ca exchange and the SAR-ESP relationship. *European Journal of Soil Science* **57**, 626-633.

Kuchenbuch R, Claassen N, Jungk A (1986) Potassium availability in relation to soil moisture. *Plant and Soil* **95**, 221-231.

Kurth E, Cramer GR, Lauchli A, Epstein E (1986) Effects of NaCl and $CaCl_2$ on cell enlargement and cell production in cotton roots. *Plant Physiology* **82**, 1102-1106.

LaHaye PA, Epstein E (1969) Salt tolerance by plants: enhancement with calcium. *Science* **166**, 395-396.

Lauchli A (1990) Calcium salinity and the plasma membrane. In 'Calcium in Plant Growth and Development'. (Eds RT Leonard, PK Hepler) pp. 26-35. (American Society of Plant Physiologists: Rockville, MD.).

Lauchli A, Stelter W (1982) Salt tolerance of cotton genotypes in relation to K/Na selectivity. In 'International Workshop on Biosaline Research: 2nd'. La Paz, Mexico. (Ed. A San Pietro) pp. 511-514. (Plenum Press, New York).

Leidi EO, Saiz JF (1997) Is salinity tolerance related to Na accumulation in upland cotton (*Gossypium hirsutum*) seedlings? *Plant and Soil* **190**, 67-75.

Lentz RD (2003) Inhibiting water infiltration with polyacrylamide and surfactants: applications for irrigated agriculture. *Journal of Soil and Water Conservation* **58**, 290-301.

Letey J (1985) Relationship between soil physical properties and crop production. *Advances in Soil Science* **1**, 277-295.

Letey J, Stolzy LH, Blank GB (1962) Effect of duration and timing of low soil oxygen content on shoot and root growth. *Agronomy Journal* **54**, 34-37.

Levy GJ, Shainberg I, Miller WP (1998) Physical properties of sodic soils. In 'Sodic Soils: Distribution, Properties, Management and Environmental Consequences'. (Eds ME Sumner, R Naidu) pp. 107-123. (Oxford University Press: Oxford, UK).

Levy R, Hillel D (1968) Thermodynamic equilibrium constants of sodium-calcium exchange in some Israeli soils. *Soil Science* **106**, 393-398.

Lindsay WL (1979) 'Chemical Equilibria of Soils.' (John Wiley and Sons: New York).

Loveday J (1976) Relative significance of electrolyte and cation exchange effects when gypsum is applied to a sodic soil. *Australian Journal of Soil Research* **14**, 361-371.

Loveday J (1980) Australian soils: the last 200 years. In 'National Soils Conference Review Papers'. Glen Osmond, S.A. (Eds TS Abbott, CA Hawkins, PGE Searle). (Australian Society of Soil Science).

Loveday J, Saunt JE, Fleming PM, Muirhead WA (1970) Soil and cotton response to tillage and amelioration treatments in a brown clay soil. 1. Soil responses and water use. *Australian Journal of Experimental Agriculture and Animal Husbandry* **10**, 313-324.

Lynch J, Lauchli A (1985) Salt stress disturbs the calcium nutrition of barley (*Hordeum vulgare* L.). *New Phytologist* **99**, 345-354.

Lynch J, Lauchli A (1988) Salinity affects intracellular calcium in corn root protoplasts. *Plant Physiology* **87**, 351-356.

Lynch J, Polito VS, Lauchli A (1989) Salinity stress increases cytoplasmic Ca activity in maize root protoplasts. *Plant Physiology* **90**, 1271-1274.

Maas EV, Grieve CM (1987) Sodium-induced calcium deficiency in salt-stressed corn. *Plant, Cell and Environment* **10**, 559-564.

Maas EV, Hoffman GJ (1977) Crop salt tolerance - current assessment. *ASCE Journal of Irrigation and Drainage Division* **103**, 115-134.

Maathuis FJM, Amtmann A (1999) K^+ nutrition and Na^+ toxicity: the basis of cellular K^+/Na^+ ratios. *Annals of Botany* **84**, 123-133.

Malik M, Letey J (1992) Pore-size-dependent apparent viscosity for organic solutes in saturated porous media. *Soil Science Society of America Journal* **56**, 1664-1667.

Marschner H (1995) 'Mineral Nutrition of Higher Plants.' (Academic Press: London).

Maser P, Gierth M, Schroeder JI (2002) Molecular mechanisms of potassium and sodium uptake in plants. *Plant and Soil* **247**, 43-54.

McCown RL, Murtha GG, Smith GD (1976) Assessment of available water storage capacity of soils with restricted permeability. *Water Resource Research* **12**, 1255-1259.

McIntyre DS (1979) Exchangeable sodium, subplasticity and hydraulic conductivity of some Australian soils. *Australian Journal of Soil Research* **17**, 115-120.

McIntyre DS, Loveday J, Watson CL (1982) Field studies of water and salt movement in an irrigated swelling clay soil. 1. Infiltration during ponding. *Australian Journal of Soil Research* **20**, 101-105.

McKenzie DC (1998) 'SOILpak for cotton growers (3rd edn).' (NSW Agriculture: Orange, NSW).

McKenzie DC, Abbott TS, Chan KY, Slavich PG, Hall DJM (1993) The nature, distribution and management of sodic soils in New South Wales, *Australian Journal of Soil Research* **31**, 839-868.

McKenzie DC, Abbott TS, Higginson FR (1991) The effect of irrigated crop production on the properties of a sodic Vertosol. *Australian Journal of Soil Research* **29**, 443-453.

McKenzie DC, Bernardi AL, Chan KY, Nicol HI, Banks LW, Rose KL (2002a) Sodicity vs yield decline functions for a Vertosol (Grey Vertosol) under border check and raised bed irrigation. *Australian Journal of Experimental Agriculture* **42**, 363-368.

McKenzie DC, McBratney AB (2001) Cotton root growth in a compacted Vertosol (Grey Vertosol). 1. Prediction using strength measurements and 'limiting water ranges'. *Australian Journal of Soil Research* **39**, 1157-1168.

McKenzie NJ, Green TW, Jacquier DW (2002b) Laboratory Measurements of Hydraulic Conductivity. In 'Soil Physical Measurement and Interpretation for Land Evaluation'. (Eds NJ McKenzie, KJ Coughlan, H Cresswell) pp. 150-162. (CSIRO Publishing: Collingwood, VIC).

McLeod IG (2001) The Effect of Waterlogging and Ion Interactions on the Development of Premature Senescence in Irrigated Cotton. Doctor of Philosophy Thesis, University of New England.

Menzies NW, Guppy CN (2000) In-situ soil solution extraction with polyacrylonitrile hollow fibres. *Communications in Soil Science and Plant Analysis* **31**, 1875-1886.

Midwood AJ, Boutton TW (1998) Carbonate decomposition by acid has little effect on the ^{13}C of organic matter. *Soil Biology and Biochemistry* **30**, 1301-1307.

Motomizu S, Wakimoto T, Toei K (1980) Spectrophotometric determination of phosphate in river waters with molybdate and malachite green. *Analyst* **108**, 361-367.

Muller F (2005) The effect of sodicity severity and depth on irrigated cotton production at Hillston, New South Wales. Masters Thesis, The University of Sydney.

Munns R (1993) Physiological processes limiting plant growth in saline soils: some dogmas and hypotheses. *Plant, Cell and Environment* **16**, 15-24.

Naidu R, McClure S, McKenzie NJ, Fitzpatrick RW (1996) Soil solution composition and aggregate stability changes by long-term farming at four contrasting sites in South Australia. *Australian Journal of Soil Research* **34**, 511-527.

Naidu R, Rengasamy P (1993) Ion interactions and constraints to plant nutrition in Australian sodic soils. *Australian Journal of Soil Research* **31**, 801-819.

Naidu R, Rengasamy P, de Lacy NJ, Zarcinas BA (1995) Soil solution composition of some sodic soils. In 'Australian Sodic Soils: Distribution, Properties and Management'. (Eds R Naidu, ME Sumner, P Rengasamy) pp. 155-161. (CSIRO Publications: Melbourne).

Nakamura Y, Tanaka K, Ohta E, Sakata M (1990) Protective effect of external Ca^{2+} on elongation and the intracellular concentration of K^+ in intact mungbean roots under high NaCl stress. *Plant and Cell Physiology* **31**, 815-821.

Nelson PN, Oades JM (1998) Organic matter, sodicity and soil structure. In 'Sodic Soils: Distribution, Properties, Management and Environmental Consequences'. (Eds ME Sumner, R Naidu) pp. 51-75. (Oxford University Press: Oxford).

NLWRA (2002) National Land and Water Resources Audit. Commonwealth of Australia, A.C.T.

Norrish K, Cornish PS, Moody PW, Jessop RS, Rummery G (2001) Soil fertility and wheat crop response to phosphorus fertiliser on Vertosols in low rainfall areas of the northern grain zone. In 'Proceedings of the 10th Australian Agronomy Conference'. Hobart. (Australian Society of Agronomy).

Norrish K, Pickering JG (1983) Clay minerals. In 'Soils: An Australian Viewpoint' pp. 281-308. (CSIRO/Academic Press: Melbourne/London).

Northcote KH (1988) Soils and Australian Viticulture. In 'Viticulture Resources in Australia'. (Eds BG Coombes, PR Dry) pp. 61-90. (Australian Industrial Publications: Adelaide, Australia).

Northcote KH, Skene JKM (1972) Australian Soils with Saline and Sodic Properties. In 'Soil Publication 27'. (CSIRO Publications: Melbourne).

Oster JD, Jayawardane NS (1998) Agricultural Management of Sodic Soil. In 'Sodic Soils; Distribution, Properties, Management and Environmental Consequences'. (Eds ME Sumner, R Naidu) pp. 125-147. (Oxford University Press: Oxford).

Park M, Li Q, Shchevnikov N, Zeng W, Mualler S (2004) NaBC1 is a ubiquitous electrogenic Na^+-coupled borate transporter essential for cellular boron homeostasis and cell growth and proliferation. *Molecular Cell* **16**, 331-341.

Patruno A, Cavazza L, Cirillo E (2002) Experiments on Soil Sodification. *Italian Journal of Agronomy* **6**, 3-13.

Payne RW (1987) 'Genstat 5 Reference Manual.' (Clarendon Press: Oxford).

Ponnamperuma FN (1972) The chemistry of submerged soils. *Advances in Agronomy* **24**, 29-96.

Ponnamperuma FN (1984) Effects of flooding on soils. In 'Flooding and Plant Growth'. (Ed. TT Kozlowski) pp. 9-45. (Academic Press: London).

Pooviah BW, Reddy ASN (1987) Calcium messenger systems in plants. *CRC Critical reviews in Plant Science* **6**, 47-103.

Prasad A, Chattopadhyay A, Singh DV (2003) Growth and cation accumulation of mint genotypes in response to soil sodicity. *Communications in Soil Science and Plant Analysis* **34**, 2683-2697.

Qadir M, Shams M (1997) Some agronomic and physiological aspects of salt tolerance in cotton (*Gossypium hirsutum* L.). *Journal of Agronomy and Crop Science* **179**, 101-106.

Quirk JP (1978) Some physio-chemical aspects of soil structural stability: A review. In 'Modification of Soil Structure'. (Eds WW Emerson, RD Bond, AR Dexter) pp. 3-16. (John Wiley: New York).

Quirk JP (2001) The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure. *Australian Journal of Soil Research* **39**, 1185-1217.

Quirk JP, Murray RS (1991) Towards a model for soil structural behaviour. *Australian Journal of Soil Research* **29**, 829-867.

Quirk JP, Schoefield RK (1955) The effect of electrolyte concentration on soil permeability. *Journal of Soil Science* **6**, 163-178.

Rampart P, Abuzar M (2004) Geophysical tools and digital elevation models: tools for understanding crop yield and soil variability. In 'Supersoil 2004: Proceedings of the 3rd Australian New Zealand Soils Conference'. The University of Sydney. (Ed. B Singh). (The Regional Institute Ltd).

Rao DLN, Batra L (1983) Ammonia volatilisation from applied nitrogen in alkali soils. *Fertiliser Research* **13**, 209-221.

Rashid A, Rafique E (2002) Boron deficiency in cotton in calcareous soils of Pakistan 2. correction and internal boron requirement. In '17th World Congress of Soil Science'. Thailand pp. 2221-2226.

Rathert G (1982) Influence of extreme K/Na ratios and high substrate salinity on plant metabolism of crops differing in salt tolerance. *Journal of Plant Nutrition* **5**, 183-193.

Reid JR, Smith FA (2000) The limits of sodium/calcium interactions in plant growth. *Australian Journal of Plant Physiology* **27**, 709-715.

Rengasamy P (2001) National Audits of Soil Sodicity; http://www.nlwra.gov.au/archive/minimal/30_themes_and_projects/50_scoping_projects/04_methods_papers/26_Rengasamy/Sodicity.html Accessed July 2006.

Rengasamy P (2002) Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Australian Journal of Experimental Agriculture* **42**, 351-361.

Rengasamy P, Greene RSB, Ford GW (1986) Influence of magnesium on aggregate stability in sodic red brown earths. *Australian Journal of Soil Research* **24**, 229-237.

Rengasamy P, Greene RSB, Ford GW, Mehanni AH (1984) Identification of dispersive behaviour and the management of red-brown earths. *Australian Journal of Soil Research* **22**, 413-431.

Rengasamy P, Olsson KA (1991) Sodicity and soil structure. *Australian Journal of Soil Research* **29**, 935-952.

Rengasamy P, Olsson KA (1993) Irrigation and sodicity. *Australian Journal of Soil Research* **31**, 821-837.

Rengasamy P, Sumner ME (1998) Processes involved in sodic behaviour. In 'Sodic Soils: Distribution, Properties, Management and Environmental Consequences'. (Eds ME Sumner, R Naidu). (Oxford University Press: Oxford).

Reuter DJ, Robinson JB (1986) 'Plant Analysis: An Interpretation Manual.' (Inkata Press: Melbourne).

Richards LA (1954) 'Diagnosis and Improvement of Saline and Alkali Soils (Handbook 60).' (United States Department of Agriculture: Washington).

Rochester IJ (Unpublished) Uptake of nutrients by cotton growing in sodic alkaline soils. *Unpublished.*

Rochester IJ, Constable GA, MacLeod DA (1991) Mineral N dynamics in a fallow grey clay. *Australian Journal of Experimental Agriculture* **31**, 237-244.

Rochester IJ, Rea M, Dorahy C, Constable GA, Wright PR, Deutscher S (1998) 'Nutripak - a practical guide to cotton nutrition.' (Australian Cotton CRC/ CSIRO Publishing).

Rosolem CA, Schiochet MA, Souza LS, Whittacker JPT (1998) Root growth and cotton nutrition as affected by liming and soil compaction. *Communications in Soil Science and Plant Analysis* **29**, 169-177.

Rubio F, Gassman W, Schroeder JI (1995) Na^+ driven K^+ uptake by the plant K^+ transporter HKT1 and mutations conferring salt tolerance. *Science* **270**, 1660-1663.

Russell EW (1973) 'Soil Conditions and Plant Growth.' (Longman Group Limited: London, England).

Russell JS, Kamprath EJ, Andrew CS (1988) Phosphorus sorption of subtropical acid soils as influenced by the nature of the cation suite. *Soil Science Society of America Journal* **52**, 1407-1410.

Ryan S, Abuzar M, Imhof M, Rampart P (2001) The use of multi-sourced remote sensing data for mapping soils and key soil properties of Victoria. In 'Geospatial Information and Agriculture Conference'. Perth, Western Australia.

Schachtman DP, Bloon AJ, Dvorak J (1989) Salt-tolerant *Triticum * Lophopyrum* derivatives limit the accumulation of sodium and chloride under salt stress. *Plant, Cell and Environment* **12**, 47-55.

Schachtman DP, Reid RJ, Ayling SM (1998) Phosphorus uptake by plants: from soil to cell. *Plant Physiology* **116**, 447-453.

Schachtman DP, Schroeder JI (1994) Structure and transport mechanism of a high-affinity potassium uptake transporter from higher plants. *Nature* **370**, 655-658.

Shabala S, Shabala L, Van Volkenburgh E (2003) Effect of calcium on root development and root ion influxes in salinised barley seedlings. *Functional Plant Biology* **30**, 507-514.

Shainberg I, Caiserman A (1971) Studies on Na/Ca montmorillonite systems 2. The hydraulic conductivity. *Soil Science* **111**, 277-281.

Shainberg I, Warrington D, Laflen JM (1992) Soil dispersibility, rain properties and slope interaction in rill formation and erosion. *Soil Science Society of America Journal* **56**, 278-283.

Shukla UC, Mittal SB, Gupta RK (1980) Zinc adsorption in some soils as affected by exchangeable cations. *Soil Science* **129**, 367-371.

Singh YV, Swarup A, Gupta SK (2002) Effect of short-term waterlogging on growth, yield and mineral composition of sorghum. *Agrochimica* **46**, 231-239.

Slavich PG, Petterson GH (1993) Estimating the electrical conductivity of saturated paste extracts from 1:5 soil water suspensions and texture. *Australian Journal of Soil Research* **31**, 73-81.

So HB, Aylmore LAG (1993) How do sodic soils behave? Effect of sodicity on soil physical behaviour. *Australian Journal of Soil Research* **31**, 761-777.

So HB, Cook GD (1987) Measuring dispersion of clay soils. In "Effects of Management Practice on Soil Physical Properties'. Queensland Department of Primary Industries Conference and Workshop Series QC87006'. Brisbane. (Eds KJ Coughlan, PN Troung) pp. 102-103.

So HB, Cook GD (1993) The effect of slaking and dispersion on the hydraulic conductivity of clay soils. *Catena Supplement* **24**, 55-64.

So HB, Kopittke PM, Menzies NW, Bigwood RC (2004) Measurement of exchangeable cations in saline soils. In 'Supersoil 2004: Proceedings of the 3rd Australian New Zealand Soils Conference'. University of Sydney, Australia. (Ed. B Singh). (The Regional Institute Ltd).

Soil Survey Staff (2003) 'Keys to Soil Taxonomy, Eighth Edition.' (United States Department of Agriculture, Soil Conservation Service, USA).

Sojka RE, Surapaneni A (2000) Polyacrylamides in Irrigated Agriculture. National Program for Irrigation Research and Development.

Speirs S (2005) Characterising soil structural stability and form of sodic soil used for cotton production. Doctor of Philosophy Thesis, The University of Sydney.

Suarez DL, Rhoades JD, Lavado R, Grieve CM (1984) Effect of pH on saturated hydraulic conductivity and soil dispersion. *Soil Science Society of America Journal* **48**, 50-55.

Sumner ME (1993) Sodic soils: New perspectives. *Australian Journal of Soil Research* **31**, 683-750.

Takano J, Kyotaro N, Yasumori M, Kobayashi M, Gajdos Z, Miwa K, Hayashi H, Yoneyana T, Fujiwara T (2002) Arabidopsis boron transporter for xylem loading. *Nature* **420**, 337-340.

Till AR, McArthur GS, Rocks RL (1984) An automated procedure for the simultaneous determination of sulfur and phosphorus and of radioactivity in biological samples. In 'Proceedings of Sulfur 84'. Alberta, Canada pp. 649-660. (Sulfur Development Institute of Canada (SDIC), Calgary, Canada).

Trought MCT, Drew MC (1980a) The development of waterlogging damage in wheat seedlings (*Triticum aestivum* l.) 2. *Plant and Soil* **56**, 187-199.

Trought MCT, Drew MC (1980b) The development of waterlogging damage in wheat seedlings (*Triticum aestivum* L.). 1. Shoot and root growth in relation to changes in the concentration of dissolved gases and solutes in the soil solution. *Plant and Soil* **54**, 77-94.

Trought MCT, Drew MC (1980c) The development of waterlogging damage in wheat seedlings (*Triticum aestivum* L.). 2. Accumulation of nutrients by the shoot. *Plant and Soil* **54**, 187-199.

Trought MCT, Drew MC (1980d) The development of waterlogging damage in young wheat plants in anaerobic solution cultures. *Journal of Experimental Botany* **31**, 1573-1585.

Tucker BM (1972) A proposed new reagent for measuring the cation exchange properties of carbonate soils. *Australian Journal of Soil Research* **23**, 633-642.

USSL (1954) 'Diagnosis and Improvement of Saline and Alkali Soils.' (USDA, U.S. Govt. Printing Office: Washington DC.).

Walkley A and Black I A (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci*ence **37**, 29–38.

Wallace A, Wallace GA, Abouzamzam AM (1986a) Amelioration of sodic soils with polymers. *Soil Science* **141**, 359-362.

Wallace A, Wallace GA, Abouzamzam AM (1986b) Effects of excess levels of a polymer as a soil conditioner on yields and mineral nutrition of plants. *Soil Science* **141**, 377-380.

Weimberg R, Lerner HR, Poljakoff-Meyber A (1983) Induction of solute release from *Nicotania tabacum* tissue cell suspensions by polymixin and EDTA. *Journal of Experimental Botany* **34**, 1333-1346.

Whitbread AM (1996) The effects of cropping system and management on soil organic matter and nutrient dynamics, soil structure and the productivity of wheat. Doctor of Philosophy Thesis, University of New England.

Wiengweera A, Greenway H (2004) Performance of seminal and nodal roots of wheat in stagnant solution: K^+ and P uptake and effects of increasing O_2 partial pressures around the shoot on nodal root elongation. *Journal of Experimental Botany* **55**, 2121-2129.

Wiengweera A, Greenway H, Thomson CJ (1997) The use of agar nutrient solution to simulate lack of convection in waterlogged soils. *Annals of Botany* **80**, 115-123.

Willett IR (1982) Phosphorus availability in soils subjected to short periods of flooding and drying. *Australian Journal of Soil Research* **20**, 131-138.

Willett IR (1983) Oxidation-reduction reactions. In 'Soils: An Australian Viewpoint' pp. 417-426. (CSIRO/Academic Press: Melbourne/London).

Willett IR, Cunningham RB (1983) Influence of sorbed phosphate on the stability of ferric hydrous oxide under controlled pH and E_h conditions. *Australian Journal of Soil Research* **21**, 301-308.

Williams CH, Raupach M (1983) Plant nutrients in Australian soils. In 'Soils: An Australian Viewpoint'. (Ed. C Division of Soils) pp. 777-794. (CSIRO/Academic Press: Melbourne/London).

Woodruff JR (2004) Interpretation of Soil and Plant Analyses for Boron in Southern Crops. In 'Southern Nutrient Management Conference'. Olive Branch, MS.

Wright D, Raiper I (2000) An assessment of the relative effects of adverse physical and chemical properties of sodic soil on the growth and yield of wheat (*Triticum aestivum* L.). *Plant and Soil* **223**, 277-285.

Wright PR (1999) Premature senescence of cotton (*Gossypium hirsutum* L.) - Predominantly a potassium disorder caused by an imbalance of source and sink. *Plant and Soil* **211**, 231-239.

Yates WJ (1972) Factors affecting the structural instability of clay soils in the Moree area, N.S.W. Masters Thesis, University of New England.

Yeates SJ, Constable GA, McCumstie T (2002) Developing management options for mepiquat chloride in tropical winter season cotton. *Field Crop Research* **74**, 217-230.

Yeo AR (1998) Molecular biology of salt tolerance in the context of whole-plant physiology. *Journal of Experimental Botany* **49**, 915-929.

Yeo AR, Lee KS, Izard P, Boursier PJ, Flowers RJ (1991) Short and long term effects of salinity on leaf growth in rice (*Oryza sativa* L.). *Journal of Experimental Botany* **42**, 881-889.

Yermiyahu U, Nir S, Ben-Hayyim G, Kafkafi U (1994) Quantitative competition of calcium with sodium or magnesium for sorption sites on plasma membrane vesicles of melon (*Cucumis melo* L.) root cells. *Journal of Membrane Biology* **138**, 55-63.

Yermiyahu U, Nir S, Ben-Hayyim G, Kafkafi U, Kinraide TB (1997) Root elongation in saline solution related to calcium binding to root cell plasma membranes. *Plant and Soil* **191**, 67-76.

Zhong H, Lauchli A (1993) Spatial and temporal aspects of growth in the primary root of cotton seedlings: effects of NaCl and $CaCl_2$. *Journal of Experimental Botany* **44**, 763-771.

Appendix

Appendix 1: Selected soil properties of a Grey Vertosol from Narrabri, NSW

Soil type[a]	Collection Site	Crop Rotation	Clay[b] (%)	pH[c]	EC[d] (dS/m)	CEC[e] (cmol/kg)	ESP (%)	Colwell P[f] (mg/kg)	Carbonate[g] (%)	Organic C (%)[h]
Grey Vertosol	'ACRI' Narrabri	Cotton – Cereal	52	7.35	0.7	38.0	2.5	42	0.05	1.1

(Isbell 1996)[a]; [b]dispersion and sedimentation; [c]1:5 soil:solution ratio in H_2O; [d]saturation extract; [e]1.0 M NH_4Cl; [f](Colwell 1966); [g](Midwood and Boutton 1998); [h] (Walkley and Black. 1934).