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**PHOSPHORUS INFLUENCE ON THE RESPONSE OF PASTURE
PLANTS TO SALINITY**

A thesis submitted in fulfilment of the requirements for the award of the degree

DOCTOR OF PHILOSOPHY

From

**UNIVERSITY OF WOLLONGONG
AUSTRALIA**

BY

KANJANARAT CHO-RUK

ENVIRONMENTAL SCIENCE

DECEMBER 2003

CERTIFICATION

I, Kanjanarat Cho-Ruk, certify that this thesis is my own work and has not been submitted for acquiring qualifications at any other institutions. I also declare that the contents of this thesis are from my personal studies unless otherwise indicated or acknowledged. This thesis is submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in Environmental Science Unit, University of Wollongong, Australia.

Kanjanarat Cho-Ruk

December 2003

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ABSTRACT

Soil salinity is a growing global problem, as the presence of salts in soils is known to impact on the growth of various plants. One feasible means suggested for limiting the impacts of salinity is the use of nutrient fertilisers. This project was initiated to assess whether the use of phosphate fertiliser would benefit the growth of pasture plant species. The interaction of P and salinity in relation to the growth of pasture plants was studied using a series of experiments. The investigations included pot experiments, using sand cultures with salinity impositions, and natural saline soils in the greenhouse, plant nutrient uptake in saline conditions, by assessing tissue mineral contents. Soil P adsorption under saline conditions was also determined to assist in explaining the results of the pot experiments.

P adsorption isotherms were measured for 3 NSW soils in various concentrations of NaCl. Different methods of salt addition (direct addition of salt solution, salt incubated soils, and different periods of time of soil in contact with salt solution) were applied to the studied soils. Salt addition increased P adsorption significantly in all 3 soils. However, there was no significant difference in P adsorption when varying the concentrations of salt (0.003-0.12mol/L NaCl). Salinity increased P adsorption in soils but further increases in NaCl concentration did not increase P adsorption. Extended contact time between soils and NaCl solution appeared to reduce the overall P adsorption capacity in soils.

Plants from 5 pasture species were grown in pots with suboptimum, optimum, and high P levels in saline cultures to compare yields. Salinity affected plant seed germination in all species by reducing the numbers of sown seeds germinated and slowing the germination rate. At the highest salinity level used (12 dS/m), all seeds failed to germinate. Considering the germination rate, the salt tolerance ranked from

ryegrass, birdsfoot trefoil, orchard grass = red clover and white clover. Under normal experimental conditions in sand culture, 25 ppm P as NaH_2PO_4 solution was determined as the optimum P level for all pasture species. Insufficient and excessive levels of P caused injury in plants and affected yields and plant tissue mineral contents.

Ryegrass with various salinity treatments (0, 2, 4, 8 and 12 dS/m) showed that salinity reduced ryegrass yields significantly as the degree of salinity was increased despite the optimum P additions (25 ppm). Salinity impacts varied during the plant growth development. When plants grew older, their salt tolerance improved, and the plants showed more tolerance to salinity as they reached maturity. Salinity also reduced P uptake by ryegrass plants.

Plants responded positively up to certain limits to P additions (17 and 25 ppm) in non-saline treatments. In saline treatments, plants responded differently over the whole range of added P. Positive results were obtained when P was added up to 17 and 25 ppm. Further increases in added P did not increase plant yields; indeed, negative results or no change were obtained. Therefore, over a wide range of studied P, plants showed both positive and negative effects as well as no effect of P in saline conditions. Increasing added P increased P content in plant tissues. In all treatments where salinity was imposed, salinity increased Na and Cl contents in plant tissues. However, the effects of salinity on other mineral constituents were highly crop specific.

In a natural saline soil culture, there was no mass response of red clover and ryegrass yields to P additions. Increased P level in the treatments did not show any plant capacity to overcome the effect of salinity. Plants still showed symptoms of salinity injury, such as yellowing and leaf burn. Salinity therefore was the main

retarding factor. Increasing P fertilisation in a natural saline soil increased P content in plant tissues.

This current study indicates that the interactive effects between salinity and P depended on P range and salinity level. Plants responded differently over a wide range of P at low and medium levels of salinity. However, P additions at any concentration were not able to assist plants overcome the effects of salinity at extremely high saline conditions, as poor soil structure and plant physiological disorders limited plant responses to added P. Limiting the development of soil salinity is the major way to reduce its impact on crop production.

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LIST OF SPECIAL NAMES OR ABBREVIATIONS

P = Phosphorus

EC = Electrical Conductivity

EC_{se} = EC_e = Electrical Conductivity of soil extract

dS/m = decisiemens/meter

ads = adsorption

ESP = Exchangeable Sodium Percentage

SAR = Sodium Adsorption Ratio

CEC = Cation Exchange Capacity

Mha = million hectares

ha = hectare

mL = millilitre

L = Litre

g = gram

mM = millimol

mm = millimetre

ppm = part per million

µm = micrometre

nm = nanometre

rpm = revolutions per minute

µS/cm = microsiemens/centimetre

**PHOSPHORUS INFLUENCE ON THE RESPONSE OF PASTURE
PLANTS TO SALINITY**

CHAPTER 1

INTRODUCTION

1.1 Introduction

The purpose of this research project was to investigate the interactions of salinity and phosphorus (P) fertilisation of pasture species. By using pot experiments involving application of different levels of P and salinity, the information produced provides indication of the interactions between salinity and fertility for pasture species. P sorption by soils is regarded as a limitation for plant use and in pasture management, the P requirement of soils, especially in salt-affected soils, is of concern. P adsorption isotherms were determined with and without sodium chloride to confirm the effects of salts on P adsorption. The significance of this research is not only the management of salt-affected soils, but also in the improvement of yield with optimum amounts of added fertilisers to cause least impacts on surface waters by leaching or surface run off. This research project was set on a small scale in the glasshouse, but the results can be applied to the field situation and provide a guide for soil salinity management in pastures.

This chapter provides general information on the nature of the problem, the background to the study and outlines the objectives of the study.

1.2 Nature of the Problem and Background of the Study

Soil salinity (where soil properties and behaviour are affected by the presence of water -soluble salts) is one of the World's most serious environmental problems (Ghassemi et al., 1995). It threatens many land uses and is one component of land degradation. The accumulation of soluble salts in soils has adverse effects on agriculture in arid and semi-arid areas worldwide, under both irrigated and non-irrigated conditions (Greenway, 1962a). These regions are characterised by long, dry summers and short winters, with typically, low rainfall and high rates of evaporation. In almost all dry areas receiving less than 500 mm annual precipitation or with precipitation-to-evaporation ratios of 0.75 or less, salts may accumulate in a lower horizon of the soil or be transported to a lower drainage area where the water evaporates leading to salt accumulation. Therefore, salt accumulation is most severe in low-lying soils due to the factors of position and permeability (Thorne and Peterson, 1954). These areas also include extensive areas of rangeland and dry land farming (Brady and Weil, 1996).

Salinity problems have occurred in the Murray-Darling Basin in Australia, the Colorado Valley in North America, and the Steppes of Russia. In Asia, along the Indus in Pakistan, the Yellow River in China, and the North-East of Thailand (**Figure 1.1**), salinity has posed problems, partly due to natural phenomena and partly induced by human activity. In Egypt, the Nile Valley area had been irrigated for 5,000 years without salinity problems, but after the construction of Aswan Dam, salinity began building up in soil profiles due to the obstruction of water movement, preventing salts being washed away (NSW Agriculture, 1993).

Please see print copy for Figure 1.1

Figure 1.1. The North eastern part of Thailand where salt-affected areas are found (Ghassemi et al., 1995).

Soil salinity and drought conditions are major environmental constraints that limit crop area, yield and total production in arid regions. Therefore, soil fertility is considered as a limiting factor under saline conditions (Balba, 1995). Mashhady et al. (1982) reported that the areas prone to salinity and drought cover about 27.9% of the World's land area. Arid and semi-arid lands are widely utilised for agriculture; to

maintain production on these agricultural lands or increase the agricultural potential, irrigation, therefore, is utilised. Some irrigation systems have brought about remarkable increases in the salt level of already saline soils, while, in other areas, irrigation water transports salts from watershed areas to cultivated lands. The use of excess water in these dry lands and their mismanagement often raise the groundwater table and this can result in salt-affected soils. Not only are additional salts introduced by irrigation water, but immobilised salts are also released in the soil through mineral dissolution and weathering. **Figure 1.2** demonstrates how salinity may arise and expand in the landscape. The loss of water through evapotranspiration and the concentration of dissolved salts in soil solution, as well as various soil amendments, such as, fertilisers, manures, composts, liming materials, or plant protection materials will intensify the hazards of salinity (Gupta and Abrol, 1990; Wolf, 1999). Poor soil drainage can also cause serious problems as salts from various sources accumulate and cannot escape. The area of irrigated land damaged by salinity in the five major countries using irrigation, estimated for the mid-1980s, is given in **Table 1.1**.

1.2.1 Types of Soil Salinity

There are two types of soil salinity. Primary salinity is salinity occurring naturally, such as salt accumulation resulting from weathering of parent materials, or one-time submergence of the soil under seawater (Ghassemi et al., 1995), or some areas containing natural salt deposits (Poljakoff-Mayber, 1975). Salt lakes, salt marshes and salt flats are natural saline areas. Secondary salinity refers to salinisation, that results from human activities, especially land development and agriculture (Queensland Department of Natural Resources, 1997).

Please see print copy for Figure 1.2

Figure 1.2. The Salinity regime (Beal, 1993).

Table 1.1. Irrigated land damaged by salinity in the five major countries using irrigation and the World, estimated for the mid-1980s (Ghassemi et al., 1995).

Please see print copy for Table 1.1

Salt stored in the soil profile, mobilised by extra water provided by human activities such as irrigation, or land clearing, is the cause of the secondary salinity.

The excess water raises the watertable carrying with it dissolved salts from lower in the soil profile, and when the watertable comes close to the soil surface, water is evaporated, leaving salts to form soil salinity. Secondary salinity is divided into three categories; watertable salting, irrigation water salting, and erosion scalding (**Figure 1.3**) (Queensland Department of Natural Resources, 1997). It can be difficult, however, to separate the different types of salinity because the secondary salinity is often effectively primary salinity, which has been accelerated or enhanced by human activities. There are now many areas showing secondary salinity that have been affected by primary salinity in the past. Reeve and Fireman (1967) indicated that about one-third of the World's 1,200,000 km² of irrigated land is affected by secondary salinity. An estimate of secondary salinity in irrigated areas worldwide is presented in **Table 1.2**.

The impacts of soil salinity range from a slight effect on plant growth to an extreme one where cultivation is unlikely to occur. The total area of salt-affected soils in the World is about 9,548,000 km² (McTainsh, 1993). They occur in many areas of the World: Europe, Asia, Africa, North America, South America, Central America, and Australia. Buringh (1977) estimated that the World loses about 1.6 Mha of arable land to salinity every year. Dunkhovny (1978) estimated the total area of saline lands under irrigation to be about 50 Mha, or almost 20 percent of all irrigated land. Kovda (1983) estimated the areas affected by soil salinity, both natural and human-induced, to be about 1 to 1.5 Mha a year. The area of salt-affected soils in different regions is shown **Table 1.3**.

Please see print copy for Figure 1.3

Figure 1.3. Type of salinity (Taylor, 1991).

Table 1.2. Global estimate of secondary salinisation in the World's irrigated lands (FAO, 1989; Ghassemi et al., 1995).

Please see print copy for Table 1.2

Soil salinity causes environmental, economic and social damage. It reduces soil productivity, affects crops and vegetation, and consequently transforms productive land to barren land leading to loss of habitat and reduction of biodiversity. Salinity also causes damage to water resources by increasing the amount of salt in rivers affecting water supplies for drinking and irrigation. Infrastructure is affected by salt through the destruction of bitumen and concrete (Commonwealth of

Australia, 2001). There is no accurate estimate of the economic damage worldwide resulting from soil salinity, but figures of more than several billion dollars per year have been predicted (Ghassemi et al., 1995). The social cost of salinity is also difficult to predict. Soil salinity causes the movement of the farm populations and reduction in income due to lower crop yields.

Table 1.3. Area of salt-affected soils in different regions (Beek et al., 1980; Brady and Weil, 1996).

Please see print copy for Table 1.3

Extensive areas of land are used for intensive cultivation, during which some nutrients are removed from soils leading to loss of soil productivity. Sustained irrigation agriculture is also critical for food and fibre production to support the growing human population (Hillel, 1991). The increase of the world population is also creating additional pressure on agricultural areas; therefore, to provide enough food for the world population is a major challenge. As there is a large area of salt-affected soils worldwide, many efforts are being made to “reclaim” these soils. One of the major ways proposed to “reclaim” these salt-affected lands is by fertilisation.

The use of fertilisers is one mechanism that can assist those lands to produce satisfactory yields. Nevertheless, the use of fertilisers on salt-affected lands is different from the situation on normal soils due to larger amounts of fertilisers that often have to be applied (Bernstein et al., 1974). However, high rates of fertilisation tend to increase soil salinity as well as yields, consequently, increased soil water stress, i.e., yield benefits from high rates of fertilisation, may be somewhat diminished by increased soil salinity (Lunin and Gallatin, 1965b). Therefore, the optimum levels of fertilisation are desirable in application to saline soils as they can contribute to soil salinity. The economic aspects have also to be considered in fertiliser application on these lands. In many research projects, salt tolerant crops have been fertilised to determine the effects of salinity under different conditions of fertility. However, in salt affected areas, high rates of fertilisation may not be economical, especially in parts of the World where the availability of fertilisers is limited.

Not only have many studies been conducted on the response of agronomic species to saline substrates, which is important to the utilisation of arid lands, but research has also been carried out into soil salinity and fertilisation, especially with the major limiting nutrients (N, P, and K). For example, pot culture studies have indicated that generous use of fertilisers may offer a means of temporarily “living with” moderate salt problems where the soil has serious plant nutrient deficiencies (Bains and Fireman, 1968). However, previous results have often been inconsistent or even contradictory. Fertilisation has been reported to increase, decrease or have no effect on plant yields under saline conditions. Due to the complex nature of the problem, therefore, further studies are required. Bernstein et al. (1974) indicated that when high salinity is the dominant limiting factor, increasing fertility would be

relatively ineffective compared to decreasing salinity. The present study investigated the interaction effects of salinity and P fertilisation on pasture plants. The reason for studying pasture plants is that areas used for pasture production have been and are being affected by salinity. Can these areas be maintained in reasonable productivity by the use of fertilisers? Accordingly, salt tolerance of grasses and legumes is of interest together with fertiliser application.

Sand culture and pot experiments were conducted in this present study. Sand and solution culture studies are useful in evaluating the influence of relatively high concentrations of various ions upon the protoplasm of the plant (Wadleigh et al., 1951). Pot experiments also seek to obtain information on certain problems, i.e., the effect of specific ions from salts, the effects of salt distribution in the root zone, etc. As the plants are grown in the medium, the salt content of the sand and its distribution within the pots, and the moisture must be controlled (Yaron et al., 1973).

1.3 Aims

The objectives of the study were:

- To observe the growth of pasture species in variable environments of P and salinity to determine the most suitable P treatments for pasture production under saline conditions;
- To assess the capacity of fertilisers to reduce salinity impacts on plant growth;
- To better understand the interaction between salinity and P fertility in pasture production systems;
- To examine the effect of salinity on P adsorption by soils; and,

- To provide the recommendations on the management of salt-affected soils and the improvement of pasture yields under saline conditions.

1.4 Thesis Outline

The remainder of this thesis contains 5 chapters. Chapter 2 contains a literature review, Chapter 3 describes the experimental materials and methods, Chapter 4 presents the results and discussion, and Chapter 5 contains conclusion and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The aim of this chapter is to provide an overview of the background information in the wider context of soil salinity and P and their relations by reviewing the relevant literature. Soil salinity effects and the roles of P, in soils and plants, are presented. Finally, some background information on the pasture plants used in this study is presented.

2.2 Soil Salinity

Salinity is regarded as a problem when the concentrations of sodium chloride, sodium carbonate, sodium sulphate or salts of magnesium, are present in excess amounts in soils (Poljakoff-Mayber and Gale, 1975). Feigin (1985) concluded that soil salinity develops when the concentrations of Na, Cl, HCO_3 , SO_4 ions and B in the soil solution are high enough to affect plant growth. Boron is present as H_3BO_3 or borate salts. Salinity poses a problem in agriculture and normally occurs in arid and semi-arid climates, where rainfall is not sufficient to transport salts out of the plant root zone. It is not only low rainfall, but also high evaporation rates that lead to high concentrations of salts in soils. Soluble salts produce harmful effects on plants by increasing both the salt content of the soil solution and the degree of saturation of the exchange complex of the soil with exchangeable sodium (Shainberg, 1975). There are three types of salt-affected soils; saline soils, sodic soils (non-saline alkaline soils) and saline alkaline soils. **Table 2.1** presents the

classification of salt-affected soils originally for use or devised in the USA (U.S. Salinity Laboratory Staff, 1954).

Table 2.1. U.S. Salinity Laboratory classification of halomorphic soils (salt-affected soils) (U.S. Salinity Laboratory Staff, 1954).

Please see print copy for Table 2.1

As noted above, saline soils are soils containing soluble salts in sufficient quantities to interfere with the growth of most crop plants, but they do not contain enough exchangeable sodium to dramatically alter soil characteristics. Plant growth is affected by salinity depending on the plant species, soil texture and water holding capacity, and the salt composition. In Australia, sodium and chloride are usually the dominant ions in saline soils. For this reason, soil is defined as saline, when the chloride content, expressed as sodium chloride, exceeds a certain percentage of the dry weight of the soil (McTainsh and Boughton, 1993). Northcote and Skene (1972) used the chloride content in defining a soil as being saline; for a surface soil (A horizon), when the chloride content as NaCl exceeds 0.1% by weight in sands and loams, or more than 0.2% NaCl in surface clay loams and clays, or more than 0.3% NaCl in the B horizon, this gives a saline soil. Kearney and Schofield (1936) suggested that saline soils are soils containing more than 0.1% salt. The U.S. Salinity Laboratory Staff (1954) defined saline soils as those have an electrical conductivity

(EC) of the saturation extract (EC_{se}) greater than 4 millimhos/cm (or 4 dS/m) or 1.5 for a 1:5 soil: water extract (see **Appendix 1** for the EC units and the comparison of EC_{se} and $EC_{1:5}$) (Charman and Murphy, 1991) and exchangeable sodium percentage (ESP: the extent to which the exchange complex is saturated with sodium ions) less than 15. Higher salinity classes are defined for soils with saturation extracts having conductivities of more than 8 and 12 millimhos/cm (Troeh and Thompson, 1993). White (1997) suggested that soils are saline when the soluble salt concentration exceeds 2500 mg/kg.

Due to the presence of excess salts and the absence of significant amounts of exchangeable sodium, saline soils are normally flocculated due to high-charge exchange cations and high electrolyte concentrations (salt) in the solution (McBride, 1994). Water infiltration and permeability of saline soils are equal to or higher than those of similar non-saline soils. The pH of saline soils is usually less than 8.5 (Hayward and Wadleigh, 1949). A white crust of salts often occurs on the soil surface in dry weather (Black, 1957).

Sodic soils contain exchangeable sodium in a quantity sufficient to interfere with the growth of most crop plants, but they do not contain appreciable quantities of soluble salts. Sodic soils have the ESP greater than 15, and the conductivity of saturation extract less than 4 millimhos/cm. Exchangeable sodium affects the physical and chemical properties of the soil. As the exchangeable sodium increases, a high proportion of exchangeable sodium attached to clay mineral exchange sites weakens the bonds between soil particles. As a result, the clay particles in the soil tend to swell and disperse when soil is wetted. The dispersed colloids may move into the soil pores and prevent water flow. Consequently, the hydraulic conductivity (ability of soil to conduct water) of the soil is decreased, and this also causes poor

aeration. Moreover, such soils often exhibit surface sealing, and are susceptible to erosion by wind or water. Soil characteristics include being dense, cloddy, structureless and having reduced water storage. The pH of these soils often ranges from 8.5 to 10 due to hydrolysis of adsorbed sodium in the absence of electrolytes in the soil solution (Queensland Department of Natural Resources, 1999). When these soils occur in small, irregular areas in arid or semi-arid regions, they are called *slick spots* (Thorne and Peterson, 1954). The management of sodic soils is often overlooked because it is a natural phenomenon and often sodicity occurs in the subsoil.

Sodicity and salinity often occur together. However, they are distinctively different soil properties. Salinity is a measure of the salt concentration in the soil solution and sodicity is a measure of the type of cations present in the soil cation exchange sites (Commonwealth of Australia, 2001).

Saline alkaline soils are defined as soils containing sufficient exchangeable sodium to interfere with the growth of most crop plants and having appreciable quantities of soluble salts (Thorne and Peterson, 1954). The electrical conductivity of the saturation extract is greater than 4 millimhos/cm and the ESP is greater than 15. The pH of these soils is usually below 8.5 (Black, 1957). Soil colloids are flocculated, but, when leached, they become dispersed, having a very compact structure with a low permeability as the sodium concentration is lowered. Some of the exchangeable sodium hydrolyses to form sodium hydroxide, which reacts with carbon dioxide to form sodium carbonate leading to highly alkaline conditions with a pH above 8.5 (Thorne and Peterson, 1954). Therefore, a saline alkali soil, when leached without calcium to replace sodium, leads to the formation of sodic soil (nonsaline-alkali soil) as the removal of soluble salts from the high sodium-saturated

soil colloids allows the soils to deflocculate and form a compact structure as discussed earlier.

An exchangeable sodium percentage (ESP) of 15 corresponds approximately to a sodium adsorption ratio of 13. ESP reflects the saturation of the exchange complex with Na related to the other cations present. The sodium adsorption ratio (SAR) is the relation between sodium and divalent cations (calcium and magnesium) in the saturated soil extract. It is used to express the relative activity of sodium in exchange reactions with soil (CSIRO, 1983; Ghassemi et al., 1995). Classification of salt-affected soils using the exchangeable sodium percentage, EC and SAR are diagrammed in **Figure 2.1** and **2.2**. Properties of saline, sodic and waterlogged soils are presented in **Table 2.2**.

The relation between ESP and CEC is presented below:

$$\text{ESP} = \text{Na}^+_{\text{ex}} / \text{CEC} \times 100$$

Where Na^+_{ex} = exchangeable ($\text{mmol}(+)\text{kg}^{-1}$)

CEC = cation exchange capacity ($\text{mmol}(+)\text{kg}^{-1}$)

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

Where Na^+ , Ca^{2+} and Mg^{2+} are soluble ionic concentrations in $\text{mmol}(+)/\text{L}$

Please see print copy for Figure 2.1

Figure 2.1. One classification system for saline, sodic, and alkaline sodic soils (Havlin et al., 1999).

Please see print copy for Figure 2.2

Figure 2.2. The classification of normal, saline, sodic and saline-sodic soils in the relation to soil pH, electrical conductivity, Sodium Adsorption Ratio (SAR), and Exchangeable Sodium Percentage (ESP), and the ranges for different degrees of sensitivity of plants to salinity (Brady and Weil, 1996).

Table 2.2. Major properties of saline, sodic and waterlogged soils relevant to plant survival and growth, modified from Marcar and Khanna (1997).

Please see print copy for Table 2.2

a = EC_e , Electrical conductivity of water extracted from a saturated soil paste

b = ESP = Exchangeable Sodium Percentage, under Australian conditions, sodic
soils have $ESP > 6$

n.a. = Not applicable

Rising watertables at the ground surface cause dryland salinity and these rising watertables can also cause waterlogging and inundation. Therefore, high concentrations of salt are often accompanied by waterlogged conditions (NSW Agriculture & Fisheries, 1988). However, waterlogging and dryland salinity may or may not be related. Some underground parts of the landscape carry freshwater and some saline water. As the underground channels fill or intersect the ground surface, the fresh streams cause waterlogging, the saline streams result in salinity problems (Kingwell, 2003). Waterlogging of the surface soil limits gaseous diffusion, causes nutrition problems and increases plant diseases. Therefore, under such situations, plants must be able to withstand poor aeration or high watertables, in addition to their ability to withstand relatively high concentrations of salts (Thorne and Peterson, 1954). The development of waterlogged soils is mainly associated with low-lying lands with poor physical condition and internal drainage. A restrictive layer, which is close to the soil surface, can cause waterlogged conditions; consequently, salts can accumulate (Keren, 2000). **Figure 2.3** shows the waterlogged condition which is a sign of soil salinity. Unlike the problems resulting from soil sodicity, which are chemical in nature, the problems resulting from soil alkalinity can be physical as well as chemical.

Soil chemical problems in alkaline soils result from reduced availability of P, K and most of the micronutrients (especially Fe). High salt concentrations reduce the response of grain and vegetable crops to fertiliser applications as discussed subsequently in **Section 2.6** (Troeh and Thompson, 1993).



Figure 2.3. Waterlogging in soil caused by salinity.

2.3 Australian Salt-Affected Lands

2.3.1 Extent of Saline Soils

Australia is the driest continent in the World with an average annual rainfall of 420 mm, of which about 87% is lost to the atmosphere by evaporation and transpiration (Australian Water Resources Council, 1976). Being considered as medium to low rainfall areas, therefore, salt accumulation is extensive (Thorne and Peterson, 1954). Sarre (1999) divided soil salinity into two broad groups: dryland salinity (occurring on land not subject to irrigation) and irrigated land salinity. Both kinds of soil salinity result from excess salts and affect the productivity of land by limiting plant growth. The effects of soil salinity, as noted by Charman and Murphy

(1991), are adverse effects of salts on plant growth (more details in **Section 2.4**), the effect on water quality, low vegetation cover leading to high erosion rates (**Figure 2.4**), soils high in sodium developing to sodic soils as calcium and magnesium ions are replaced by sodium cations on the clays, high saline soil solutions having high potential to mobilise heavy metals and other potentially toxic substances in soils.

Please see print copy for Figure 2.4

Figure 2.4. Soil erosion resulting from soil salinity (Commonwealth of Australia, 2001).

The naturally saline lands are related to the occurrence of geomorphic basins with closed drainage and low hydraulic gradients. About 5.3% of the land area of Australia is naturally saline (Northcote and Skene, 1972). **Figure 2.5** presents the distribution of salt-affected areas in Australia. However, many salinity problems in Australia have arisen from human activities, particularly those that alter the natural

distribution of water and salt in the landscape. Additionally, natural salinity has also been exacerbated by changes in land use since European settlement (Commonwealth of Australia, 2001).

Please see print copy for Figure 2.5

Figure 2.5. The distribution of normal, saline, saline-sodic, and sodic soils in Australia (Northcote and Skene, 1972).

Land clearing is the main cause of rising groundwater tables, especially the clearing of deep-rooted native plants and their replacement by shallow rooted crops or annual pasture plants which use less water, therefore, affecting the rate and

amount of water use in the landscape (Martin and Metcalfe, 1998). This results in more water reaching groundwater system. The groundwater rises to near the surface in low-lying areas carrying dissolved salts from the soil and bedrock material through which it travels. As the saline groundwater comes close to the soil surface (within 2 m), salt enters the plant root zone. In the areas where the groundwater does not carry sufficient amount of salt with in, the waterlogging of the plant root zone itself can damage vegetation (Chan, 2001). **Figure 2.6** illustrates a raising groundwater table due to land clearing and **Figure 2.7** demonstrates the result of land clearing.

Inefficient irrigation practices, seepage from irrigation channels and inadequate surface drainage have contributed to a rise in watertables in the irrigation areas, and consequently to salinity problems. Therefore, changes to the Australian landscape have resulted in the widespread and rapid growth of soil salinity problems. About 840 km² of irrigated soils and 1,970 km² of dryland soils are affected by secondary salinisation.

However, not only in the irrigation areas, but also the excess salt content in soils of non-irrigated agricultural land has become significant since the 1940s, due to large areas of land having been cleared, followed by the development of high technology farming equipment (Williamson, 1990).

Please see print copy for Figure 2.6

Figure 2.6. The raising of groundwater table due to land clearing for 2 Western Australian catchments: the Wights catchment was cleared in 1976-77, while the Salmon catchment remained forested (Peck, 1983).

McTainsh and Boughton (1993) noted that about 37% of the total area of salt-affected soils in the World is present in Australia (about 2.5 Mha). In Western and South Australia, Victoria, and NSW, salinised soils occupy about 55% of the total area (Poljakoff-Mayber and Gale, 1975). In Queensland, approximately 0.35% of the total area was estimated to be affected by naturally occurring saline soils (Northcote and Skene, 1972). In Victoria, there are reports of large areas of salt-affected soils and some areas have the potential to be salt prone (Victoria Parliamentary Committee Report, 1984). In Western Australia, about 30% of the landscape is now regarded as being at risk of salinity; in the near future, 70 to 90% of low-lying lands will possibly be affected by salinity (National Dryland Salinity Research, Development and Extension Program, 1999).

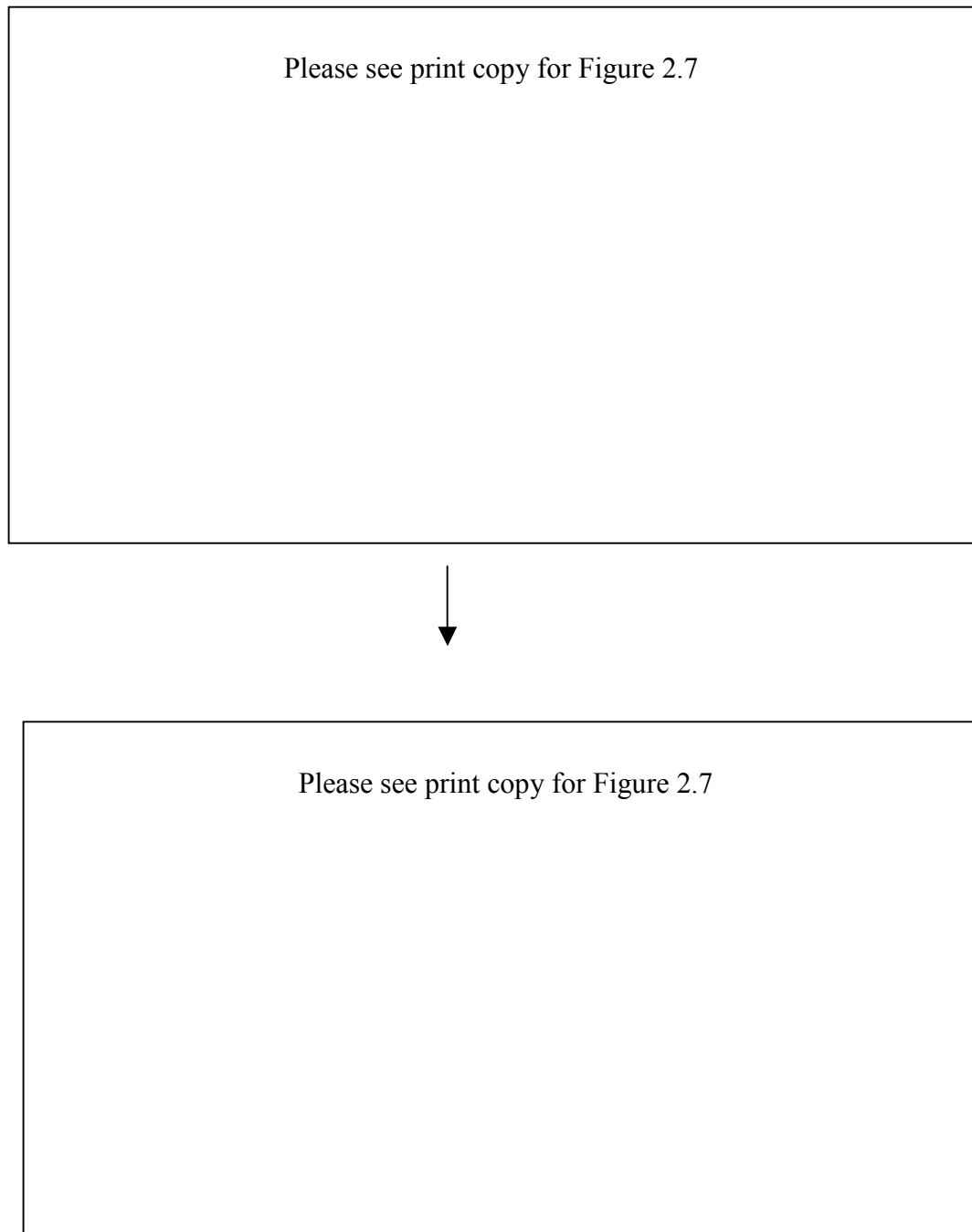


Figure 2.7. How land clearing can cause soil salinity (Chan, 2001).

Looking at the whole picture, dryland salinity is defined as a major cause of land degradation in Australia (McTainsh and Boughton, 1993). Farmland affected by salinity is expanding at a rate of 3-5% a year, with an estimated annual cost of \$270

million (Bennett, 1998). The Year 2000 Australian Dryland Salinity Assessment has revealed that areas considered being at risk or affected by dryland salinity cover approximately 5.7 Mha. It has also been estimated that, in 50 years' time, this area may increase to 17 Mha (Commonwealth of Australia, 2001). **Table 2.3** presents data on areas of secondary salinity in Australia.

In Australia, salinity has affected the farmers (who are among the first group to be impacted), through salinisation of rivers and agricultural land. Biodiversity, together with regional and urban infrastructure, such as water supply, roads and buildings, are also at risk from salinity (Commonwealth of Australia, 2001).

Table 2.3. Area of land affected by dryland salinity in Australia (Bennett, 1998).

Please see print copy for Table 2.3

* The potential area affected at equilibrium is the likely area to be affected if the current levels of salinity are not treated.

Not only is the area of saline soils extensive, but Northcote and Skene (1972) also noted that 25 to 30% of Australian soils are sodic soils (defined in **Section 2.2**). Rengasamy and Olssen (1991) estimated that 2 million km² of Australia soils were affected by sodicity. The presence of excess exchangeable sodium or the absence of specific salts reduces water infiltration causing poor soil permeability, leading to crust formation, which can interfere with seedling emergence. In addition to effects on plant growth, waterlogging and inundation are observed in salt-affected soils as discussed later.

Recent data collected from several sources reveal slightly different information on salinity extent on different areas of salt affected in Australia (see **Table 2.4**).

2.3.2 Sources of Salts

Salts found in the landscape come from various sources, such as:

- Irrigation water;
- Mineral dissolution of immobilised salts, weathering of the mineral parts of soil and rock (Taylor, 1991);
- Loss of water by evapotranspiration causing dissolved salt concentration in soil solution leading eventually to precipitation of salts;
- Fertilisers;
- Decaying organic matter;

Table 2.4. A comparison of estimates salinity extent (Kingwell, 2003).

Please see print copy for Table 2.4

Note: GRDC = Grains Research & Development Corporation

PMSEIC = Prime Minister's Science Engineering and Innovation Council

NLWRA = National Land and Water Resources Audit

ABS = Australian Bureau of Statistics

WA= Western Australia, NSW = New South Wales, Vic = Victoria,

SA = South Australia, and Qld = Queensland

a = excludes Queensland as estimates were not available

- Atmospheric salt decomposition, which is an important source of salts along the coasts. Cyclic salt is ocean salt carried inland and deposited by rainfall or wind. Wind turbulence over the sea creates aerosols of salt crystals, which later can be deposited on land as dry deposition, or they may be condensed as rain and fall on land. This is an important source of chlorides. It is estimated that salt, derived from the sea in this way, adds about 100-200 kg/ha/year for distances up to 50-150 km from the sea (White, 1997). In western parts of Australia and in the Murray-Darling Basin, salt accumulation has been estimated at about one million tons per year or 10 kg/ha/year (NSW Agriculture, 1993);
- Fossil or connate salts present in soil profiles. Salts mainly come from fossil marine sediments from earlier geological times, e.g., some areas of western NSW were once below sea level (NSW Agriculture, 1993).

Human activity changes in hydrology caused by clearing of deep-rooted vegetation or the use of excess irrigation water can result in saline groundwater rising close to the soil surface (White, 1997), which has been discussed earlier. These processes change or affect the distribution of salts.

The significance of each source in contributing soluble salts depends on the natural drainage conditions, soil properties, water quality, soil water, and agronomic management practices followed for crop production (Gupta and Abrol, 1990). Peverill et al. (1999) also noted that the degree of salt accumulation in a soil depends on the degree of leaching of soil (its permeability), the presence of vegetation (evapotranspiration), and the amount and seasonal distribution of rainfall.

2.4 Effects of Salinity on Plant Growth

In arid and semi-arid areas, excessive salt in soil is detrimental to plant growth. There are many effects of salts on plant growth, mainly from one or more of three different sources:

- Direct physical effects of salts in preventing water uptake;
- Direct chemical effects of salts in disturbing plant nutrition and metabolism; and,
- Indirect effects of salt in altering soil structure, permeability, and aeration (Thorne and Peterson, 1954).

These effects are discussed below.

2.4.1 Effect of Salts on Plant Absorption of Nutrients

Competition between ions

Ions in a soil solution can affect the absorption of one another by a plant (Mengel and Kirkby, 1987). The uptake of one is often decreased when the concentration of another is increased as seen in saline soils, where the presence of several ions, both cations and anions, which have different charges, can influence the absorption process of nutrients. Potassium (K) is absorbed more rapidly than other alkali cations, which have smaller hydrated ions. An effect of soil solution Na on the absorption of K by plants has been observed. The application of K to saline soils decreases the adverse effect of Na on plants and Balba (1995) reported that the uptake of N as NH_4 was decreased with the increase of K application.

For anions, Cl reduces the absorption of phosphate, and sulfate decreases the uptake and accumulation of P in barley and sunflower (Zhukovskaya, 1973). High

levels of NaCl reduce NO_3^- uptake leading to a nitrogen deficiency in plants (Torres and Bingham, 1973). P absorption is also decreased in presence of excess Cl or sulphate ions (SO_4^{2-}) due to anion competition effects (Balba, 1995).

Application of K, NH_4 or P fertilisers not only corrects the deficiencies of fertilisers in soils but also decreases the adverse effects of Na, Cl and SO_4^{2-} on plants (Balba, 1995). The nutritional needs of plants also vary and various types of salts present also show different effects. High Na levels are associated with decreasing levels of Ca and Mg, especially in sodic soils where these ions are held strongly. This will produce nutritional disturbances (Bernstein et al., 1974).

2.4.2 Effect of Salts on Forms of Soil Nutrients

Many studies have investigated the effects on plants of soil salinity and limiting nutrients, such as P (Cairns and Bowser 1969). The effect of soil salinity on the P solubility in soils was investigated by Lehr and Van Wesemael (1952). By using neutral salts, the soluble phosphate was depressed in the order of $\text{Na} < \text{K} < \text{Mg} < \text{Ca}$. Therefore, the availability of phosphate is higher in soil with less Ca as insoluble calcium phosphate forms in soils with high Ca content. Soluble P in soils tends always to be extremely low. In alkaline and neutral soils, P tends to be combined with Ca (Hausenbuiller, 1972).

Excess bicarbonate ions associated with high alkalinity reduce the uptake of copper, iron, manganese and zinc (Gunn et al., 1988). A similar trend was found by Maas and Nieman (1978) where high pHs lowered the availability of some nutrients, such as, Fe, Mn, Ca and Mg, by lowering their solubility. Furthermore, high pHs not only accentuate deficiencies of many microelements, but also lead to high concentrations of aluminium such as aluminate $\text{Al}(\text{OH})_4^-$ species (Bohn et al, 2001)

and nutritional imbalance, i.e., bicarbonate toxicities have been reported for some saline environments due to reduced Fe availability in high bicarbonate soils rather than bicarbonate ions themselves (Bohn et al., 2001).

Generally, the amount of N is less in salt-affected soils compared to normal soils (Stevenson et al., 1982). High pH in these soils leads to volatisation of ammonia and, due to reduced amounts of oxygen in salt affected soils (waterlogging conditions), anaerobic conditions lead to denitrification and release of nitrogen gas.

N and P are not the only major nutrients limiting crop production, K may also be limiting. The movement of soil solution to the root interface, uptake of nutrients by plants, and the utilisation of nutrients in plants affect plant growth, and soil salinity may have detrimental effects on one or more of these processes (Luken, 1962).

It is noteworthy that many studies have, however, shown ambiguous results relating to the effect of salt on soil nutrients (e.g., Maas and Hoffman, 1977; Feigin, 1985; Soliman and Farah, 1986). The reasons for these variations in the results are difficult to resolve.

2.4.3 Effect of Salts on Plant Processes

Effect on osmotic pressure

In general, the growth process of a plant takes place by uptaking nutrient and water via roots and transpiration via leaves. Both processes are complicated and several factors are involved, i.e., biological, physical and climatological factors.

Plants expend energy to extract water from the soil (overcoming the soil water potential), i.e., the energy required is greater than that with which the soil retains water. Salts in a soil solution increase the osmotic pressure, which will

restrict the uptake of water by plant roots or decrease the physical availability of water (increase the force the plant must exert to be able to extract water) (Hayward and Wadleigh, 1949; 1973; Balba, 1995). The wilting point of soils (defined as the volume of water per unit bulk volume of soil when plants wilt permanently because of a lack of extractable water in the soil (Peverill et al., 1999)) is also increased due to salt accumulation, leading to reduced water availability. The wilting point is when root cells of plants, in contact with a soil solution high in salts, tend to lose water by osmosis to the more concentrated soil solution, causing cell collapse (Brady and Weil, 1996). To avoid dehydration, plants in saline soils have to adjust the osmotic pressure at the roots (Maas and Nieman, 1978). The effects of high salt content on metabolic processes caused by low water potential include reduced protein hydration, retardation of enzymatic processes and lead to a shortage of plant building material associated with reduction in photosynthesis (Khalil et al., 1967; Mer et al., 2000). Wilson et al. (1999) showed that rice sensitivity to salinity is the result of changes in the osmotic potential gradient rather than to Cl toxicity. Balba (1995) concluded that the effects of high osmotic pressure on plant growth, especially of the cell sap, are due to the following:

- Plants have to expend more energy to grow and maintain the high osmotic pressure of sap;
- Cells such as plastids and mitochondria cannot change the osmotic pressure of their sap, and the highest osmotic pressure is likely to accompany harmful concentrations of elements, which might affect enzyme activity.

However, the kind of salt, the plant species, and the extent of salinisation are factors determining the concentration at which the cell succumbs (Brady and Weil,

1996). Hewitt (1966) noted that the injurious effects of high concentrations of salinity appear to be due to osmotic pressure rather than to Na ions.

Effect of salinity on transpiration

The rate of transpiration in plants decreases with increase in the soil salinity level. This is due to the inability of plants to absorb water from a soil solution of higher osmotic pressure than that of the cell sap. The transpiration rate of plants growing in saline conditions decreases as a result of lower absorption of water causing a decrease in the surface area of leaves, and an increase in water retained by plants (Balba, 1995). The result of salinity is thus a lowering of plant transpiration accompanied by decreased plant growth and yields. A study on beans showed the total amount of water loss by evapotranspiration decreased with increasing salinity and similar results were observed in corn and tomatoes (Lunin and Gallatin, 1965a).

2.4.4 Effect of Salts on Soil Microorganisms and their Activities

The number of microorganisms in salt-affected soils is lower than in nonsaline soils, and their activities are slower under saline conditions than in normal soils (Paliwal and Mariwal, 1972)

The nodulation of legumes, such as soybean, has been observed to be significantly reduced with the increase in salinity (NaCl) (Bernstein and Ogata, 1966).

Salinity impedes the decomposition of organic matter in saline soils, therefore, leading to insufficient release of essential elements to plants (Ravikovitch and Porath, 1967).

2.4.5 The Constraints Related to Soil Physical Conditions

Three detrimental effects of salts on plants are (Brady and Weil, 1996):

- The caustic influence of the high pH induced by the presence of sodium carbonate and bicarbonate;
- Oxygen deficiency due to breakdown of soil structure;
- The reduced available moisture supply in soils as salinity increases (Hayward and Bernstein, 1958).

As noted earlier, Thorne and Peterson (1954) indicated that salts have indirect effects in altering soil structure, permeability, and aeration. Sodic soils often have low permeability limiting plant growth (Hayward and Wadleigh, 1949). Excess exchangeable sodium (high ESP) leads to undesirable physical and chemical conditions in soils. The dispersion of clay lowers the permeability of the soil to air and water leading to oxygen deficiency and the dispersion results in the formation of dense, impenetrable surface crusts impeding the emergence of seedlings. Not only does decreased hydraulic conductivity reduce oxygen diffusion, but also the release of carbon dioxide. The reduced gaseous diffusion and permeability of water cause the accumulation of salts to toxic levels beneath saturated surface (Gunn et al., 1988; Havlin et al., 1999). Nutrition problems will also occur and tilling practices of these soils are difficult (Hausenbuiller, 1972; Balba, 1995).

2.4.6 Toxicity and Specific Ion Effects

Plant growth may also be inhibited by the presence of salts due to ion toxicity and deficiency. Chloride, sodium and boron toxicity are the most common causes of specific ion effects. The toxic levels of these three species differ considerably between plants, and are found to be highest in plants for chloride and lowest for

boron. Sulfate, bicarbonate and magnesium ions also contribute to the toxicity problems.

- *Sodium Toxicity*

Na is considered as one of the more difficult and problematic ions in soil and plant interactions. In sensitive plants, a concentration of 0.5% of dry weight will cause toxic symptoms (Yaron et al., 1973). In nonsaline sodic soils, plants suffer from excessive exchangeable sodium due to its competition with other nutrient cations and its specific deleterious effects (Balba, 1995). High sodium concentrations in soil solutions may induce Ca and K deficiencies due to high pH, and HCO₃ levels repress solubilities and concentrations of some species.

- *Chloride toxicity*

Cl toxicity appears to be similar to Na toxicity. Plant growth is inhibited by high concentrations of Cl in the soil solution due to its adverse effects, especially with high concentrations of Ca ion. This detrimental effect has been found in orchard grass (Wadleigh et al., 1951). Cl is not adsorbed by soils but moves readily with the soil water (Gunn et al., 1988). Leaf burn is caused by chloride toxicity, starting from the leaf margins and as the toxicity increases, defoliation and leaf drop may take place (Balba, 1995). Soybean (*Glycine max*, L.) has been shown to be susceptible to Cl toxicity (Eaton, 1942). A study on sesame showed leaf necrosis where plants were grown under saline conditions due to an excessive accumulation of Cl (Cerdeira et al., 1977). Cl also lowered photosynthesis activities in potatoes (Thorne and Peterson, 1954). The critical Cl concentration in plant tissue has been estimated at 0.5-1.8%, on a dry weight basis (Yaron et al., 1973).

- *Boron toxicity*

Boron (B) is an essential micronutrient needed in small amounts for plants, but excessive B is toxic to plants. Moreover, the optimum range in soil between deficiency and toxicity is very narrow (Keren, 2000). Boron occurs naturally in alkaline soils at levels high enough to cause toxicity, especially in arid and semi-arid regions, due to high soil B or B additions in irrigation water (Yaron et al., 1973; Brady and Weil, 1996; Keren, 2000). Its toxicity level is at concentrations of more than 4 mg/L, but, for sensitive crops, 0.3 mg/L is the threshold B concentration (Keren, 2000). Small quantities of boron absorbed by roots are accumulated in leaves (Yaron et al., 1973). Toxicity symptoms are yellowing, spotting on leaf tips, typical leaf burn and finally dying of leaf tissue (Balba, 1995).

- *Sulfate toxicity*

A 1% concentration of sulfate found in leaves can cause injury and is considered as a toxic level. Sulfate ion promotes the uptake of sodium (leading to toxicity) and restricts uptake of Ca (leading to deficiency) (Yaron et al., 1973). Sulfate limits activities of Ca ion and therefore, cationic intake by plants. Specific adverse effects of sulfate are related to a disturbance in the optimum cationic balance within the plant (Hayward and Wadleigh, 1949). Therefore, the harmful effect of the sulfate ion is related to disturbance of the uptake balance of cations (Thorne and Peterson, 1954).

- *Bicarbonate toxicity*

Bicarbonate can cause chlorosis similar to that caused by iron unavailability and at high concentrations can precipitate Ca in soil, increasing the exchangeable

sodium percentage and leading to a deterioration of soil structure (Yaron et al., 1973). An increased supply of CO₂ and consequently bicarbonate ions, was shown to improve the fertility of many saline soils by lowering pH and increasing P availability (Thorne and Peterson, 1954).

- *Carbonate toxicity*

Carbonate ions have been rated as highly toxic to plants. The concentration of carbonate ions is a direct function of pH and high concentrations in soils are accompanied by high exchangeable Na and often poor soil structure and aeration. So their presence makes soils unsuitable for crop production (Thorne and Peterson, 1959).

- *Magnesium toxicity*

Magnesium affects plant growth mainly by reducing Ca uptake and causing Ca deficiency. When high concentrations of Mg are present together with high concentrations of Ca, there is no specific ion effect of Mg (Yaron et al., 1973). The Mg:Ca ratio in exchangeable complex is important. Thorne and Peterson (1954) suggested that Mg is more toxic than Na and Ca.

- *Nitrate toxicity*

Nitrate ions can accumulate to toxic levels in plants. The toxicity in soils is similar, on the basis of osmotic concentration, to that of sulfate and chloride (Thorne and Peterson, 1954).

The major impact of salts in suppression of plant growth is likely to be due to the high concentration of soluble salts more than due to specific ions. Furthermore, it is accepted that the degree of toxicity of salts on plant growth depends on the type of salts; some salts are more toxic than others and some plants are able to tolerate high concentrations of salts, while others are sensitive to even low concentrations (Maas and Nieman, 1978).

Effects of salts on plants also vary with soil fertility especially when inadequate fertility limits yield (Bohn et al., 2001). The effects of individual ions have been noted, and adverse effects of soluble salts rather than those limiting the availability of moisture may be important in restricting growth of many plants. These are collectively referred to as toxic effects and include the disturbance of the nutrition and metabolism of plants.

Three phases of plant growth are influenced by salinity:

- The rate of germination is decreased through reduced water uptake (due high osmotic pressure) and ion toxicity to the embryo and seedling;
- The vegetative growth and maturation are retarded at high osmotic potentials; and,
- Yields are reduced due to nutritional deficiencies and unfavorable water relations (Hayward and Wadleigh, 1949).

Some studies have shown different degrees of salinity causing varying effects on plants. Slight salinity has reduced crop or pasture productivity by 10%, while moderate salinity can reduce productivity by up to 50% (Martin and Metcalfe, 1998).

Figure 2.8 illustrates relative crop yield in relation to soil salinity for plant salt-tolerance groupings as outlined by Maas and Hoffman (1977), and Queensland Department of Natural Resources (1997).

Shainberg and Shalhevet (1984) studied the effect of soil salinity on plants under irrigation. Crop response to salinity is usually described as a decreasing function with increase in the electrical conductivity (EC) of the soil solution. In this study, it was found that the reduction in crop yield due to soil salinity was linearly related to the electrical conductivity of the soil solution after a certain electrical conductivity threshold value was obtained:

$$Y = -bEC_e + a$$

b = slope

a = the salinity threshold value in EC_e unit

Increasing salinity caused a slow growth rate. The growth rate and leaf expansion were found to be the first affected by salt and water stress.

Please see print copy for Figure 2.8

Figure 2.8. The relative crop yield in relation to soil salinity for plant-tolerance groupings of Maas and Hoffman (1977); Queensland Department of Natural Resources (1997).

Plant anatomy and physiology are affected by soil salinity (by water restriction, nutrient uptake disturbance and ion toxicity effects) and many symptoms are similar to those caused by drought, as outlined below:

- Soil salinity affects the cell enlargement and division of plants. Salts prevent the first stage of cell division;
- Soil salinity retards plant growth by damaging growing cells and limiting the supply of essential metabolites depriving growing cells of some essential substances or conditions (Maas and Nieman, 1978);
- The size of plants, branching, and leaf size and plant anatomy are affected by salinity. Salinity causes stunting, delayed maturity, especially in younger plants and younger parts of plants (Poljakoff-Mayber and Gale, 1975);
- Shoot growth of plants suffers from salinity more than root growth as indicated by lower shoot/root ratios (Yaron et al., 1973). Leaf area in plants is reduced due to salinity (Tanji, 1990);
- Plants grown in saline conditions tend to be darker coloured and more bluish-green (purple spots or steaks) than similar plants grown under non-saline conditions. High chlorophyll contents and thick cuticle coatings are observed in plants to reduce water loss; a response to stress, hence water (osmotic stress). A lack of P hinders metabolic processes such as the conversion of sugar into starch and cellulose is also found in plants grown in salt conditions. The result of build up of sugar is the formation of anthocyanins, which show purple spots (Thompson and Troeh, 1973). Salinity also changes the structure of the chloroplasts and the mitochondria in leaves (Yaron et al., 1973);

- Leaf mottling or spots, leaf curling and incipient chlorosis (yellowing) are also seen in plants under saline conditions (Black, 1957). In severe cases, necrosis and leaf burn occur (Yaron, et al., 1973);
- Other effects: as plants have to adjust themselves to survive in the saline environments, plants will move the excess salts to vacuoles where their effects are minimized. This will take significant amounts of energy. The reduced energy affects several energy-requiring processes of N and CO₂ assimilation and protein and cytokinin synthesis. Therefore under saline conditions, plants will show poor CO₂ assimilation (decreased photosynthesis causes plant stomatal closure therefore, reducing CO₂ entering the leaves) so that carbohydrate formation is impaired (Wolf, 1999).

The hormone mechanisms must also be considered, as the balance between root and shoot hormones changes significantly under saline conditions. Reduced cytokinin production in the roots and its transport to the shoots, is caused by stress. The supply of cytokinin to the leaves increases transpiration and synthesis of some proteins leading to a reduction in the supply of root hormones to the leaves, consequently, results in reduced transpiration and growth rate. The impaired balance of shoot and root hormones results in similar symptoms as mentioned earlier, osmotic effects on growth retardation and respiration suppression under saline conditions (Yaron et al., 1973).

Briefly, plant growth is adversely affected by excess salinity and is limited by the supply of essential nutrients. The unsatisfactory growth derives mainly from inhibited or reduced physiological functions of plants, poor physical condition of the soil caused by a high exchangeable sodium percentage (ESP) or the nutritional inadequacy, interference or imbalance. The accumulation of soluble salts in the soil

reduces plant growth by osmotic inhibition of water absorption, by specific ion effects of the saline media on growth processes (direct toxicity or indirect nutritional effects), or by the combination of two.

2.5 Tolerance of Plants to Soil Salinity

Plants differ significantly in their tolerance of soluble salts, and likewise the salts differ greatly in their detrimental effects on plants. Therefore, salinity induced by different salts results in different degrees of salinity injury (Wilson et al., 1999). The associated conditions such as temperature, moisture supply, organic matter content, soil texture, and supply of nutrients influence the tolerance of plants to salts (U.S. Regional Salinity Laboratory, 1947). Maas and Hoffman (1977) concluded the factors influencing salt tolerance of plants depended upon plant, soil, water and environmental variables. Factors related to satisfactory growth of plants on salty soils are the physiological constitution of plants, the stage of development and the rooting habits.

It has been noted that older plants are more tolerant to salt affected soils than younger ones, e.g., in alfalfa plants. Some crop species are salt tolerant during later stages of growth, while others may be quite sensitive to salinity during germination (e.g., sugar beets and safflower). However, rice can tolerate a high salinity at germination but it is sensitive to salinity in the early stages of growth. Similar patterns were found in barley, wheat and corn (Maas and Hoffman, 1977). The degree of sensitivity of crops to salinity during germination is uncertain. Therefore, the germination stage of growth is not more sensitive to salts than other stages. On the other hand, soil moisture evaporation from the soil surface layers, where seeds are sown can lead to higher salt concentrations, and failure of seeds to germinate

(Balba, 1995). The effects of salts on seed germination can be attributed to the lower osmotic potential of the soil solution due to increased salt concentration (Mer et al., 2000).

Deep-rooted plants show greater resistance to salts than those which are shallow-rooted (Brady and Weil, 1996). The explanation for this is the greater water availability for deep-rooted plants.

The weather is a factor influencing soil salinity. Under hot and dry conditions, most crops are likely to have less salt tolerance (or suffer greater salt stress) than those grown under cool and humid conditions. Under hot and dry environments, plants suffer from high evapotranspiration (ET) demand. The rate of water absorption by plant roots is faster than rate of water compensation in the soil. Therefore, the soil water depletes leading to increased salt concentration around the plant roots. A study on onions, beets and beans in cool and hot locations showed different results. The order of salt tolerance changed from onions >beets >beans at the cool location, to beets >onions >beans at the hot location. It was also concluded that weather appeared to affect salt-sensitive crops to a much greater extent than salt-tolerant crops (Balba, 1995; Havlin et al. 1999).

There is a difference in the tolerance of individual plant species to salinity, i.e., plant cultivar and variety differences. Different soybean varieties differ in their Cl exclusion leading to different ability to resist salts (Havlin et al., 1999). Similar results were found in 14 varieties of rice tested for salt tolerance (Balba, 1995). The tolerance increases with the capacity to adjust to the high internal solute suction and decreases with the sensitivity to this adjustment (Black, 1957). Excretion, regulation and accumulation are mechanisms among salt tolerant plants (Balba, 1995). Therefore, the salt tolerance is related to an ability to regulate their ion uptake such

as reduced Cl uptake under saline conditions. Salt-sensitive varieties of wheat absorbed more Cl than more tolerant ones (Greenway, 1962b). **Table 2.5** presents information on the tolerance of crops to salinity and **Figure 2.9** shows the diagram of salt tolerance noted by Bernstein (1964a).

Two categories of plants are classified according to how they can grow in saline conditions: salt resistant and salt-tolerant plants. Salt-resistant plants (glycophytes) maintain growth in mildly saline soils by excluding salts at the roots; however, in extremely saline soils, glycophytes are unable to both exclude salt and obtain sufficient water for maintenance and the plant tissues are sensitive to high concentrations of salts (Queensland Department of Natural Resources, 1997). The species best adapted to saline soils are called halophytes. They are highly effective at avoiding salt uptake, and at dealing with salt accumulation in the leaves (Bennett, 1998).

Plant tolerance to salinity is assessed in two ways (Balba, 1995):

- Effects on germination given as the proportion of plants emerging from a saline soil expressed as a percentage of those emerging from non-saline soil. As noted above, crops are usually least tolerant during germination except in sugar beet. Maize, rice and wheat are sensitive at the early seedling stage and show more salt tolerance as they become mature.
- Effect on growth after emergence given as a relative yield, which is the yield of the crop grown in a saline soil, expressed as a fraction of the same crop yield in non-saline conditions.

Table 2.5. The relative tolerance of forage crops to salinity (U.S. Regional Salinity Laboratory, 1947).

Please see print copy for Table 2.5

Please see print copy for Figure 2.9

Figure 2.9. Salt tolerances in crop and pasture plants (Bernstein, 1964a).

To conclude discussion of the effects of salinity on plants: as plant growth requires the movement of essential nutrients from the soil system into the plant, i.e.,

release of nutrients from the solid phase into soil solution, movement of nutrients from the soil solution to root interface, uptake of nutrients by the plant, and subsequent utilisation of the nutrients in the plant, soil salinity may have detrimental effects on one or more of these four processes (Khalil et al., 1967).

2.6 Salinity and Fertility

Salinity has an effect on soil fertility. Fertility in the same way, affects plant salinity tolerance. However, salinity and fertility relationships are complicated. Much research has been conducted to examine the effects of fertilisation on nutrient uptake by plants, on the chemical composition of plant tissues, and on crop yield under various salinity conditions. The results of those studies have shown positive, negative and no effects of fertilisation on crops growing in saline soils (Feigin, 1985). Examples of the differing outcomes are summarised in **Table 2.6**.

The positive effects can be explained that the effects of water stress by salinity can be partially overcome when soil P levels are high (Fertiliser Industry Federation of Australia, Inc. & CSIRO Australia, 2000). Plants seem more tolerant of given salt concentrations where the P supply is held at a higher level of availability than where phosphate is at medium or low level (Thorne and Peterson, 1954).

Table 2.6. The summary of the interaction between salinity and fertility.

Please see print copy for Table 2.6

For the negative effects, it may be concluded that in a well-fertilised soil, some plants display salt effects more than plants grown under suboptimal conditions due to lack of nutrients (Taylor, 1991).

No significant change in salt tolerance with the application of fertiliser was found in beans and corn when the levels of N were increased (Lunin and Gallatin, 1965b).

From the above data, one can see that the effects of fertiliser application under saline conditions are unclear and some data are even contradictory. Some workers concluded that adverse effects of salinity on plant growth are not reduced by fertiliser applications; rather a partial response to fertilisers may be expected where nutrient deficiencies limit growth more than salt does (Bernstein, 1964b; Feigin, 1985).

Plant response to superphosphate in saline soils is negligible when nitrogen is low. The response to superphosphate was moderately positive when nitrogen was adequate. When applied to P deficient soils, N often does not increase yield as much as it does on soils with an adequate supply of P (Soliman et al., 1994; Northwest Agricultural Consultants, 2001). In saline conditions, salts have an effect on nitrogen in leaching and denitrification (Hamilton, 1972). Saline soils vary greatly in their physical properties and in the proportion of Na and Ca in solution therefore, phosphate availability is also variable. However, there is evidence that low available P is found under saline soils because of complex Ca compounds which are dominant in arid regions giving low phosphate solubility (Thorne and Peterson, 1954). In contrast, the presence of NH_4^+ creates acid environments due to nitrification and NH_4^+ uptake, thus making more P available for uptake by plants (Sharpley, 2000).

The effects of P treatment on plant salt tolerance depend on the plant species. The response is connected with the leaf's accumulation capacity for P. The salinity effect is greater with species able to accumulate large amounts of P without developing any injury (Cerdea and Bingham, 1978). In saline conditions, leaf P concentrations never exceeded 0.91% for tomato plants while sesame plants accumulated leaf P at 2.1% accompanied by leaf necrosis. In this situation, tomato plants exhibited higher salt tolerance than sesame plants (Cerdea et al., 1977).

Therefore, changes in salt tolerance by P addition to a saline substrate are related to the plants' ability to withstand salinity without suffering a decrement in yield, inherent P requirements, and plants' ability to absorb P from the substrate. The salt tolerance of plants accumulating high levels of P is reduced in at least some cases by increasing P levels in the substrate (Cerdea et al., 1977).

2.6.1 Plant Mineral Tissue Contents

Plant tissue analysis is a valuable tool in research on processes related to plant nutrition. The analysis includes the chemical evaluation of essential element concentrations in plant tissues (elements required in the plant life cycle). These elements are supplied by soil or nutrient solutions. Macronutrients - N, P, K, Ca, Mg and S are required in greatest quantities. Micronutrients - Fe, Mn, Zn, Cu, B, Mo and Cl are required in very small quantities (Plank, 1999). Toxicities of micronutrients and deficiencies of macronutrients are of concern.

Interpretation of the plant tissue analysis is often complex. The results are based on the scientific principle of using healthy plants, which contain predictable concentrations of essential elements, as indicators. The relationship between maximum yield and concentrations of essential elements is presented in **Figure 2.10**.

The interpretation index shows the growth response to increasing nutrient levels (**Figure 2.11**).

The interpretation of plant analysis data includes critical values and sufficiency ranges. Critical values are defined as the concentration at which there is 5-10% yield reduction. Injury symptoms generally appear when nutrient concentrations decrease below the critical value. Therefore, critical values are set as lower limits of sufficiency ranges. Sufficiency ranges can be identified as the values immediately above the critical value. The upper limits of sufficiency ranges provide an indicator for excessive uptake of elements (Campbell and Plank, 2000).

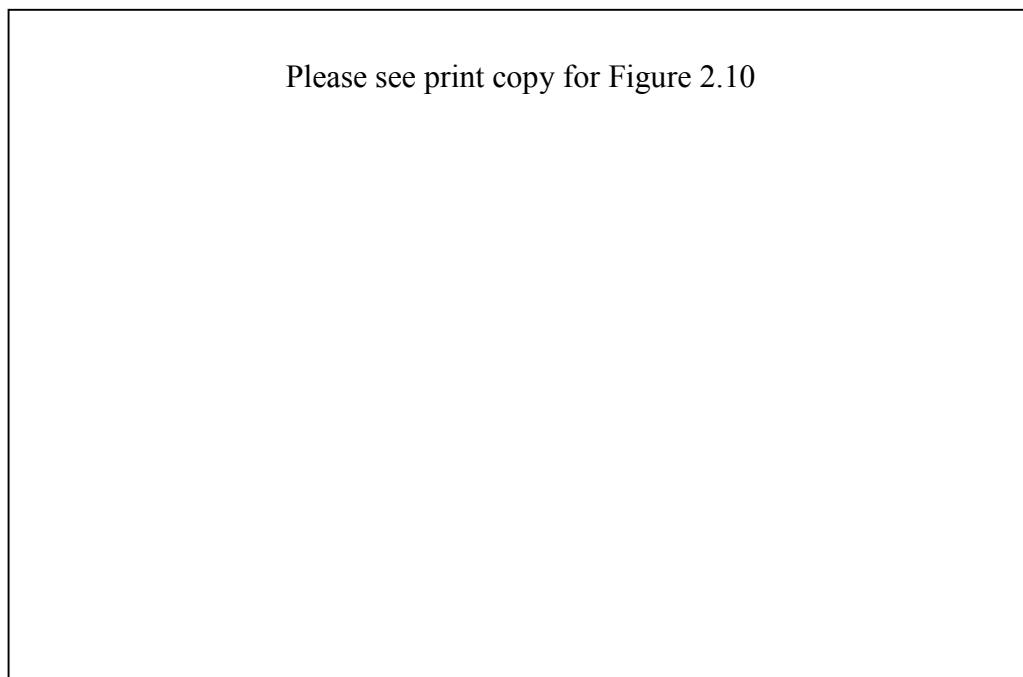


Figure 2.10. Diagram of yield and nutrient concentration (Campbell and Plank, 2000).

Please see print copy for Figure 2.11

Figure 2.11. Yield or growth in response to increasing nutrient concentration and interpretation (Campbell and Plank, 2000).

As mentioned earlier, plants can be characterised by chemical composition of developed tissues therefore, chemical analysis of plant parts is often used for diagnosis in determining fertiliser needs, poor fertility level, or excessive nutrient concentration. High salinity level in the root zone can reflect in decreasing or increasing concentrations of certain elements in plant tissues in comparison with the optimum range (Feigin, 1985). Although tissue analysis is a valuable means in research on process related to plant nutrition, interpretation of the data obtained is sophisticated. Different plant parts are not equally affected by salinity. The growth of tops is often more suppressed than that of roots, therefore top parts are often taken for analysis (Waisel, 1971). The differences also include crops or plant species, age or stage of development, plant parts, and vary with environmental conditions (Campbell and Plank, 2000). Additionally, plants vary widely in their nutrient requirements and capacity for uptake of different elements. With regard to salinity, different crops exhibit quite diverse responses to any given saline conditions.

Different properties of ions in the soil solution also produce variable effects on a given crop (Bernstein, 1964b). Therefore, when considering the effects of salinity and P on mineral compositions, they are highly crop specific.

2.6.2 Plant Composition with High Salinity

Soluble salts greater than 2% in sandy soils and 4% in clay soils are a hindrance to cultivation of many soils. The obvious detrimental results of soil salinity can be seen in plant composition. The contents of Ca, Mg, K, and Na in leaves have been observed to increase with salinity, with Na showing this effect consistently (Karmarkor and Joshi, 1969; Lunin and Gallatin, 1965b). Champagnol (1979) showed that increasing salinity reduced leaf P content of tomato, onion, barley and peas. Soliman and Farah (1986) found a decrease in P content in wheat grains with increasing salinity. Phosphorus content of bean leaves also decreased with increasing salinity where P was applied (Lunin and Gallatin, 1965b). Bernstein et al. (1974) found a similar trend in barley and some vegetable grains at high salinity and indicated that, apart from the effects of salinity on root growth of plant, salinity also had other effects on P availability due to high Ca concentrations in saline soils causing P precipitation. However, some workers found an increased P content in leaves of clover, sorghum, maize and sesame, while the others found that salinity had no effect leaf P in millet, cabbage, carrot and wheat (Ravikovitch and Porath, 1967; Bernstein et al., 1974).

The effect of salinity on plant P content is variable. Three different hypotheses have been suggested (Elleboudi, 1969; Champagnol, 1979):

1. By bringing about large increases in the ionic concentration of the substrate, salinity may reduce the relative ionic concentration of H_2PO_4^- and thus the P content of plant materials;

2. A high concentration of Na^+ can increase the amount of soluble sodium phosphate at the expense of other less soluble phosphate, leading to increased P uptake by plants;

3. Insoluble phosphates forming the solid phase of soil P provide significant plant P requirement by direct contact between the roots and the soil particle without passing through the solution phase, therefore salinity may not have an effect when the absorption is by direct contact.

2.7 P in Soils

P is at a premium in natural and agricultural ecosystems throughout the World (Brady and Weil, 1996). It has been called “the key to life” because it is involved in most life processes (Thompson and Troeh, 1973). It is classified as one of the macronutrients and a key component of cellular compounds, and is vital to both plant and animal life (Brady and Weil, 1996). It is a constituent of nucleic acids, cell membranes and the energy-carrying compound adenosine triphosphate (Peverill et al., 1999). The use of P is second only to nitrogen in importance for crop production (Holford, 1997). Due to the low solubility of P in soils, soil P is often deficient for plant growth (Black, 1957). Phosphate concentration in soil solution is usually less than 0.01 mg P/L (Sharpley, 2000). The natural supply of P in most soils is relatively small; hence, the availability is very low. Inputs of P from the atmosphere and rainfall are insignificant. However, P loss in most undisturbed

environments is very small and P concentrations are relatively stable in soils and therefore, P is often considered as a limiting nutrient.

Phosphorus is generally immobile, inaccessible, and unavailable in soils, which makes P resistant to leaching in most soils, but simultaneously, these properties lead to deficiencies of P for agriculture (Troeh and Thompson, 1993). Total P content of soils varies widely depending on soil type and region. Parent materials are often a source of soil P, but large amounts of P are lost during soil formation by leaching or erosion. However, since P is highly adsorptive, the main loss of P is due to erosion of the soil surface, when compared to leaching. The total P content of soil generally ranges from 0.02 to 0.15% depending on the parent material from which the soil has developed, and the extent to which weathering and leaching have taken place (McLaren and Cameron, 1996; Havlin et al., 1999).

Lack of adequate available P is contributing to land degradation that mostly occurs in tropical and subtropical underdeveloped countries. Phosphorus deficiency limits crop growth and can contribute to crop failures, motivating farmers to clear more land in order to survive, or shift to other areas, abandoning unproductive land.

The amount of P found in plants (0.1-0.5%) is less than that of N, K, and Ca. Plants absorb either H_2PO_4^- or HPO_4^{2-} ions. Absorption of H_2PO_4^- generally occurs at lower soil pH values, whereas uptake of HPO_4^{2-} is greater at higher values of soil pH (Havlin et al., 1999). The Fertiliser Industry Federation of Australia, Inc. & CSIRO Australia (2000), indicated that most of the P that plants absorb is as H_2PO_4^- and smaller amounts are absorbed as HPO_4^{2-} . Plant roots absorb phosphate much more rapidly when the plants are young than do the roots of the older plants. Therefore, during early plant growth stages, the concentration of available P in soil is critical (Wright et al., 1984).

One-third to two-thirds of P in plants is inorganic, and the remainder is organic. Return of the plant residues to the soil then adds a small quantity of inorganic P, which has greater solubility than the P in its original form in soil material. All forms of P in soils are, therefore, of some significance in supplying P for plants on a long-term basis (Black, 1957; Russell, 1961). Forms of P in soils are discussed in **Section 2.9.1**.

2.8 Factors Affecting P Availability to Plants

There are three main soil factors determining the ability of a soil to supply adequate P to plants (Larsen, 1967; Ozanne and Shaw, 1967):

- (1) concentration of phosphate in soil solution evaluated by the equilibrium concentration or phosphate potential, so called “intensity”;
- (2) capacity of the soil, or its ability to resist a change in the initial equilibrium concentration as P is removed by plants (estimated by measuring phosphate sorption); and,
- (3) the rate of phosphate diffusion through the soil (the rate at which phosphate may move toward the plant root).

Intensity, capacity, and diffusion factors, therefore determine the availability of P to plants. When a water-soluble fertiliser P is applied to soil, it will dissolve and increase the concentration of soil solution P. Inorganic and organic P can buffer the increase in solution P. In addition to uptake by plant roots, P can be adsorbed on mineral surfaces and precipitated as secondary P minerals. Soil microorganisms immobilise solution P as microbial P, and produce readily mineralisable P compounds (labile organic P) and organic P compounds which are more resistant to

microbial degradation. The ratio of quantity to intensity factors, called the "buffer capacity", is the maintenance of the solution P concentration (intensity) for adequate P nutrition in the plant and the ability of labile P (quantity) to replace soil solution P taken up by plants; or, in another words, is the ability of the soil solution to resist a change in its concentration as P is removed by plant uptake or added via fertilisers or organic materials (Holford, 1997; Havlin et al., 1999). The availability of P to plants is a direct function of the quantity of labile P, and an inverse function of the buffer capacity, which means the greater the buffer capacity of soil, the higher the amount of P fertiliser required to increase the level of soluble P in the soil (Amrani et al., 1999). The P cycle in soil is shown in **Figure 2.12**.



Dynamic processes involved in P cycling, therefore, are chemical and biological. Chemical processes include precipitation/dissolution and sorption/desorption. The biological processes involve immobilisation/mineralisation initiated by P uptake and decay of plants. Soil organism (fauna and flora) activities help modify the direction, extent, and rate at which these chemical and biological processes occur (Sharpley, 2000).

Soils vary greatly in their capacity to fix P. To make P in soils available to plants, the use of organic matter, silicates and lime assists in reducing the soil adsorption capacity by increasing the concentration of hydroxyl ions and with organic matter, its decomposition by microorganisms releases available P, therefore making P more available (Wolf, 1999). The use of lime in acid soils can create a favourable environment for microbial activity and also increase the solubility of P in

soils (Khasawneh et al., 1980). The P content of soil organic matter ranges from about 1-3% (Havlin et al., 1999). Millar (1958) and Troeh and Thompson (1993) indicated that the use of farmyard manure or green manure aids in making P available in soils through the dissolving effects of organic acids (anions) capable of replacing H_2PO_4^- in adsorption sites. Moreover, organic manure can improve soil physical properties and supply plant nutrients (Balba, 1995). Bower et al. (1951) found that favourable effects of manure addition to salt-affected soils were an improvement in soil structure and an increase in infiltration.



Please see print copy for Figure 2.12

Figure 2.12. Schematic representation of P cycle in different forms in soil (Havlin et al., 1999).

2.9 P Problems in Soil Fertility

There are three main problems concerning P and soil fertility. First, the total P content of soils is low and is usually less than one-tenth to one-fourth that of N, and one-twentieth that of K. Second, P in soils is found in forms or compounds that

are mostly unavailable for plant uptake due to being highly insoluble. Third, when soluble sources of P are added to soils, i.e., fertilisers or manure, they are fixed (or changed into unavailable forms) and they, thus, become insoluble species (Brady and Weil, 1996). The fixation reactions of P in soils are discussed in detail in **Section 2.10**. Organic P is an important factor in supplying P to plants in highly weathered soils, i.e., Ultisols and Oxisols. In contrast, in less weathered soils, i.e., Mollisols and Vertisols, inorganic forms of P play an important role in P fertility (Brady and Weil, 1996).

The following paragraphs provide some further information on P in soils and its availability to plants.

2.9.1 Forms of P in Soils

P minerals, e.g., apatites, are significant in nature, and the most abundant are combined with Ca and fluorine. Total soil P is divided into two broad fractions, organic and inorganic forms. The inorganic forms include the soluble ions (H_2PO_4^- and HPO_4^{2-}) discussed in **Section 2.7**, (Larsen, 1967; Thompson and Troeh, 1973), and minerals like apatite, $\text{Ca}_5(\text{PO}_4)_3\text{F}$. In the mineral apatite forms, P is tightly bound, but much soil P is in organic forms acting as a major source of P for microorganisms and mesofauna (White, 1997).

2.9.1.1 Organic P in Soils

Organic P constitutes about 20 to 80% of the total P in surface soil horizons (Corbett, 1969; Brady and Weil, 1996). Soil organic P decreases with depth and the P content of soil organic matter ranges between 1 to 3% (Havlin et al., 1999). Three main groups of organic P compounds are found: (1) inositol phosphates, (2) nucleic

acids and (3) phospholipids. The mineralisation of organic P leads to soluble P compounds being released during the decomposition of organic residues and humus. The result of the mineralisation is inorganic phosphate ions which can be absorbed by plants, adsorbed onto soil particles, or fixed into insoluble forms by reaction with iron, aluminium, manganese, and calcium in soils (Brady and Weil, 1996). Therefore, P availability decreases with time, and the process by which P is rendered unavailable is called “phosphate fixation” (White, 1997). However, in some circumstances, where there is a lot of organic matter cycling in soils, P is continuously made available in the soil.

2.9.1.2 Inorganic P in Soils

Inorganic P compounds are often divided into two groups; (1) those containing Ca and (2) those containing iron and aluminium (and, sometimes manganese). As a group, the Ca-phosphate compounds are more soluble as soil pH decreases; therefore, they tend to dissolve and disappear from acid soils. On the other hand, at higher pH, Ca phosphates are stable and very insoluble; hence they are present in neutral to alkaline soils. The iron and aluminium phosphates have very low solubility in strongly acid soils, and become more soluble as soil pH increases due to the precipitation of iron and aluminium as oxyhydroxides or other low-solubility compounds. In addition, as soil pH decreases, Al and Fe become more mobile (soluble) and more available to react with soluble P thus rendering added soluble P less plant available.

2.9.2 Effects of Organic and Inorganic P in Soil

Based on the availability of P to plants, phosphate in soil is divided into two components; labile P and non-labile P. The labile P is P on soil particle surfaces that can be readily desorbed to give phosphate ions in solution. The non-labile P is P occluded within oxyhydroxide coatings on surfaces, or held in insoluble compounds and organic matter (White, 1997).

Soil properties control the forms and solubility of P components. There are many factors affecting the amount of P in soils. The organic matter content is important as soil organic P accounts for high percentage of total P in soil. The pH helps to determine P availability and the optimum pH for P availability in soils are between 6 and 6.5 (Corbett, 1969). The P content of the clay fraction usually exceeds that of the coarser particle-size fractions. Therefore, the percentage of P in soils generally increases as the texture becomes finer (Black, 1957). Thompson and Troeh (1973) suggested that cultivation and climate also have direct effects on the P content in soils.

2.10 P Fixation

Excluding the biotic factors, the concentration of P in the soil solution and its movement are controlled by 2 phenomena:

- (1) The solubility of P-containing minerals; and,
- (2) The fixation or adsorption of phosphate ions on the surfaces of soil particles.

P fixation is described as any change that the soluble phosphate undergoes in contact with the soil, which reduces the amount that plant roots can absorb (Wild, 1950). Available P can combine with other elements to form very insoluble

compounds, which plants cannot break down. Both added (fertiliser) as well as native P can combine with other elements resulting in this situation (Corbett, 1969).

2.10.1 Sorption Reactions

P sorption and phosphate retention mean the removal of phosphate from solution by soil or by a soil constituent (Wild, 1950). The retention of phosphate at a surface of a solid is called phosphate adsorption or sorption, and the retention of phosphate within a solid phase is called phosphate absorption.

Phosphate sorption occurs by:

(A) Electrostatic bonding to charged surfaces of soil particles (physical sorption or electrostatic adsorption). Physical adsorption is generally a long-ranged interaction generated as a result of electrostatic and van der Waals forces between the ions in solution and the charged surface.

(B) The covalent bonding of phosphate ions to oxyhydroxides of iron (Fe) and aluminium (Al) and to some aluminosilicate clays. This mechanism, called “Chemisorption”, has been described by the chemical coordination of the phosphate ions onto the surface of metal ions. It is a very close ranged attractive mechanism via chemical bonding rather than by electrostatic forces. An increase in P sorption with increasing Al and Fe oxyhydroxides is found especially in acidic soils (Havlin et al., 1999; Peverill et al., 1999). Labile inorganic P as H_2PO_4^- and/or HPO_4^{2-} may significantly be adsorbed by mineral surfaces when the surface has a net positive charge, therefore H_2PO_4^- and other anions are attracted to it. P ions also adsorb to the Fe/Al oxyhydroxide surface by interacting with OH^- and OH_2 groups on the mineral surface. The replacement of OH^- and OH_2 groups that are attached to a metal ion with

phosphate ion is one form of chemisorption and is also known as anion or ligand exchange. When the orthophosphate ion is bonded through one Al-O-P bond, the H_2PO_4^- is considered as *labile* and can be readily desorbed from the mineral surface to the soil solution. However, when two Al-O bonds with H_2PO_4^- have formed, a stable six-member ring is formed. Accordingly, desorption is more difficult and the H_2PO_4^- is generally considered *non-labile* (see **Figure 2.13**) (Havlin et al., 1999).

(C) Surface precipitation is the mechanism where phosphate ions are removed from solution due to reaction with a specific cation that results in the formation of an insoluble solid (Sample et al., 1980).



Please see print copy for Figure 2.13

Figure 2.13. Mechanism of P adsorption to Al/Fe oxyhydroxide surface (McLaren and Cameron, 1996).

2.11 P Sorption Isotherm Equations

A P adsorption isotherm is used to describe the equilibrium relationship between the amount of adsorbed species (retained at the surface) and dissolved species at a given temperature (Dandy and Morrison, 1978). The soil-phosphate solution interaction is not a true equilibrium. After an initial rapid approach to the pseudo-equilibrium position, the soil continues to take up phosphate very slowly for long periods (Munns and Fox, 1976). Surface adsorption includes physical adsorption, chemisorption and anion exchange (Sample et al., 1980).

Some authors consider that adsorption isotherms can be divided into 3 regions (e.g., Muljadi et al., 1966) (**Figure 2.14**):

Region I: The adsorption isotherm rises steeply and remains close to Y-axis at low phosphate concentration ($<1 \times 10^{-4}$ mol/L). This region represents sites with a very high affinity for phosphate.

Region II: This region starts approximately at 10^{-4} mol/L when isotherm becomes convex to the Y-axis.

Region III: The adsorption isotherm becomes parallel to the X-axis and occurs at medium to high concentrations (10^{-3} to 10^{-4} mol/L).

Sorption isotherm equations were developed from simple dynamic models of gas-solid interfaces. However, they also can explain liquid-solid interfaces. Several equations have been used to explain P adsorption in soils, e.g., Freundlich and Langmuir equations. The equations describe the relationship between the quantity of P adsorbed per unit soil weight (normally in grams of soil) and the concentration of P in solution (Havlin et al., 1999).

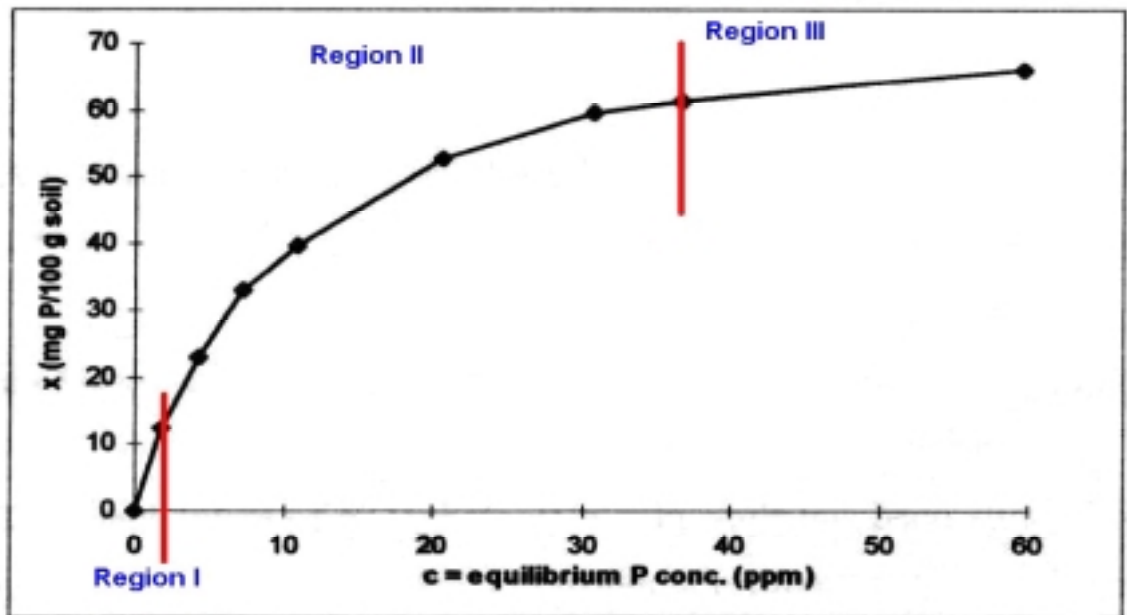


Figure 2.14. Typical P sorption isotherm in soil plotting between the amount of P sorbed (x), against equilibrium P concentration (c).

The Freundlich equation is:

$$x = ac^{1/n}$$

In linear form, the equation can be written as:

$$\log x = \log a + (1/n)\log c$$

where x is the amount of P adsorbed per unit weight of soil, c is the concentration of P in solution, and a and n are constants varying between soils (Larsen, 1967). This equation does not include a maximum adsorption capacity, therefore, it is only useful with low solution P concentrations (Havlin et al., 1999). The energy of adsorption decreases as the amount of adsorption increases.

On the other hand, the Langmuir isotherm involves a maximum adsorption capacity and it is described as:

$$x = abc / (1+ac)$$

$$\log x = \log (abc) - \log (1+ac)$$

where x , c , and a are defined as before, and b is the adsorption maximum. The P adsorption maximum in the Langmuir equation implies that a monolayer of P ions is adsorbed on the surface of mineral, which occurs at relatively higher solution P concentrations than described by the Freundlich equation. This equation suggests that further increases in solution P concentration do not increase P adsorption. Therefore, this equation is normally used to quantify P adsorption maxima (Havlin et al., 1999), noting that a slow P uptake may continue after initial saturation of surface sites.

The Langmuir Equation is based on the assumption that the energy of the adsorption does not vary with the surface coverage, therefore providing a relatively constant energy of adsorption (Bache and Williams, 1971; Bohn et al., 2001). The Equation may be written in a simple way as:

$$\frac{c}{x} = \frac{c}{x_m} + \frac{1}{kx_m}$$

The plot of c/x against c presents a straight line as shown in **Figure 2.15 (A)** of slope $1/x_m$ with an adsorption maximum at x_m , and k is a constant referring to the bonding energy obtained from the intercept. The Langmuir equation is found to be linear for phosphate concentrations ranging from 0.5×10^{-4} to 5×10^{-4} mol/L. Wider ranges can be seen in **Figure 2.15 (B)** where there is no well defined maximum and the bonding energy is not constant (Gunary, 1970; Bache and Williams, 1971).

Please see print copy for Figure 2.15

Figure 2.15. P adsorption isotherms plotting between c/x against c , presenting (A) the straight line expected from Langmuir Equation and (B) a curve typical of soils (Bache and Williams, 1971).

2.12 Factors Influencing P Sorption in Soils

As mentioned earlier, sorption of phosphate affects the availability of P to plants and cost-effectiveness of applied P fertilisers. Several factors influence the ability of soils to absorb P, including soil physical and chemical properties (Millar et al., 1958; White, 1981; Brady and Weil, 1996; Holford, 1997; Havlin et al., 1999):

- Soil mineral concentrations, these factors include: iron (Fe), aluminium (Al), and manganese (Mn) (especially the oxyhydroxides);
- Clay content or the nature and surface area of the soil particles;
- pH;
- Extent of P saturation;
- Organic matter;

- Time;
- Temperature;
- Moisture content; and
- Effect of salts, which is the main aspect of this present study (see **Section 2.12.9**)

2.12.1 Oxyhydroxide Content

The type of soil mineral surfaces affects the P adsorption and desorption reactions. Fe/Al oxyhydroxides have the capacity to adsorb large amounts of P from solution. High concentrations of iron and aluminium oxyhydroxides, therefore, are associated with high phosphate sorption in soils (Holford, 1989). Iron/aluminium oxyhydroxides are present as discrete particles in soils or as coatings or films on other soil particles. The less crystalline or the more amorphous the oxyhydroxides in soils, the larger their P fixation capacity, because of their greater surface areas (Havlin et al., 1999; Sharpley, 2000). Wild (1950) noted that the water-solubility of the phosphate in superphosphate was reduced by the presence of iron and aluminium compounds; the same situation also occurs in soils. Wild (1950) also confirmed that the removal of iron and aluminium oxyhydroxides from soils reduced phosphate sorption.

2.12.2 Nature and the Quantity of Clay Present

Wild (1950) and Sharpley (2000) stated that the retention of phosphate is greatest in clays (fine particles) due to surface area effects; large surface areas have a greater tendency to retain phosphate than small surface areas. The retention decreases as the particle size increases. Sanchez and Uehara (1980) also noted that

the mineralogy of the clay contained in the soil and the amount of clay determined the amount of P adsorption.

Clay type also contributes directly to the amount of P sorbed. Kaolinite clays show higher capacity to adsorb P than montmorillonite, partly due to the associated higher amounts of Fe/Al oxyhydroxides particularly at low pH values (Singh and Gilkes, 1991), and partly due to the fact that kaolinite clays have larger numbers of exposed OH groups in the Al layer. Such groups become positively charged and sorb P especially at low pH values (Singh and Gilkes, 1991; Havlin et al., 1999).

2.12.3 pH

The effect of pH on P fixation of soils is usually observed at very low and very high soil pHs. Phosphate fixation is lowest (the availability to plants is highest) when soil pH is between 6.0 and 7.0 (Brady and Weil, 1996). Havlin et al. (1999) also noted that P availability in most soils is at maximum near pH 6.5 (see **Figure 2.16**). At low pH, there is a retention occurring from the reaction with soluble Fe/Al or Fe/Al oxyhydroxides and precipitation as AlPO_4 and FePO_4 . However, as pH increases, the activity of Fe and Al decreases, resulting in lower P adsorption/precipitation, and leaving higher P concentrations in the solution. At pH value above 7, Ca precipitates P as Ca-P minerals and P availability therefore decreases (McLaren and Cameron, 1996). In acidic soils, P occurs in forms of Al and Fe phosphates, however, in neutral and alkaline soils, it is more likely to form as Ca and Mg phosphates or adsorbed on the surfaces of Ca and Mg carbonates (Holford, 1997). Lime application to acidic soils can increase the solubility of P, but overliming can decrease P solubility because of the formation of more insoluble Ca-P minerals.

Nevertheless, when P is fixed as compounds of Ca and Mg, it is more available than when fixed as compounds of Fe and Al (Millar et al., 1958).

Please see print copy for Figure 2.16

Figure 2.16. Soil pH effect on P adsorption and precipitation (Havlin et al., 1999 after Stevenson, Cycles of Soil, p250, John Wiley & Sons, 1986).

2.12.4 Extent of P Saturation

The extent of P saturation affects adsorption. There is higher P adsorption in soils when there is little P initially is adsorbed on the mineral surfaces. P application as fertiliser to soils results in increased adsorption, subsequently the decreased potential for additional P adsorption. When all potential P adsorption sites are saturated, further adsorption will not occur, leading to most effective use of P fertiliser (Havlin et al., 1999), but also the possibility of losses by runoff and movement to groundwater. Therefore, the amount of P sorbed by soils depends on the number of sites available for reaction for the added P (Holford, 1989).

2.12.5 Organic Matter

Organic matter has been recognised as having an effect on P sorption in soils by increasing the availability of P in 4 ways:

- 1) The formation of organophosphate complexes that plants can easily utilise;
- 2) Anion replacement of H_2PO_4^- on adsorption sites, whereby organic acid anions produced by plant roots and by microbial decay, are attracted to positive charges and hydroxyls on the surfaces of clays and oxyhydroxides;
- 3) Humus coatings on Fe/Al oxyhydroxides forming a protective cover leading to reduced P adsorption. Large humic molecules can adhere to the surfaces of clays and metal oxyhydroxide particles, masking the P-fixation sites and preventing them from interacting with P ions in solution;
- 4) An increased amount of organic P mineralised to inorganic P.

Certain organic acids and similar compounds can react with Al and Fe to produce stable organic complexes called chelates. When chelated, these metals are unavailable for reaction with phosphate ions in solution. The extent of organic matter influence on P adsorption depends on the nature of the organic matter, and the amount of iron and aluminium associated with it (Brady and Weil, 1996; Dilli, 1999).

2.12.6 Time

There is a time effect with P adsorption as the adsorption process consists of at least 2 reactions of different rates. Generally, it is found that there is an initial rapid reaction followed by a much slower reaction (Havlin et al., 1999). This results in the rate of P exchange for anions on the surface of Fe/Al oxyhydroxides being

significantly rapid. However, the formation of covalent Fe-P or Al-P bonds on Fe/Al oxyhydroxides and the precipitation of P compounds are relatively slower reactions but create a tightly bound P complex inhibiting the availability of P to plants. The change from labile P to non-labile P over time results in bi-dentate bonding (from 1 O - metal bond to 2).

2.12.7 Temperature

Higher soil temperatures increase the rate of P adsorption and desorption. The rate of soil mineralisation of P from soil organic matter and crop residues by microorganism activity is increased at higher temperatures, up to an optimum around 35 °C. Additionally, the warmer climates often give rise to soils with higher contents of the Fe/Al oxyhydroxides (Wild, 1950; Havlin et al., 1999). Rationally, soils in warmer climates usually have higher P adsorption than those of temperate climates.

2.12.8 Moisture Content

Changes in soil moisture content affect chemical and physical properties of soils, which influence the ability of soil to sorb P.

Under waterlogged conditions or after flooding, the availability of P is increased, mostly due to the conversion of Fe^{3+} -phosphate to more soluble Fe^{2+} -phosphate. This results from the reduction of the number of sites to which P can tightly bind. In this form (Fe^{2+} -P bound), P is more readily extractable. Additionally, the hydrolysis of Al/Fe phosphate is also involved (Brady and Weil, 1996). Drying of the soil increases P adsorption by increasing the accessibility of phosphate ions to adsorption sites on the mineral surfaces (Dilli, 1999), and by converting all iron present to Fe^{3+} forms.

2.12.9 Effects of Salts and Ionic Strength

Numerous papers have been published on the impact of changing solution conditions on P sorption in soils. This literature is briefly discussed in the following paragraphs.

Bolan et al. (1986) has stated that when P is adsorbed by soil, the amount adsorbed varies with the concentration and nature of the electrolyte in the supporting solution. Al Falih (2001) reported that increased salinity increased P adsorption in soil. However, inconsistent outcomes have been reported on the influence of salt and ionic strength on P retention by soils. Possible sources of the disagreement in the literature are likely due to be other factors that contribute to P adsorption in soils, e.g., pH alteration, specific electrolyte concentrations in the soil solution, nature of the cation, equilibrium time and temperature (Bowden et al., 1980; Bar-Yosef et al., 1988). Despite the inconsistencies, some agreement has been noted in attempting to explain this interaction.

Herein, there are two aspects to explain the effects of salts on P adsorption. 1) Effect of overall electrolyte concentration, and 2) Effect of particular cationic species on P adsorption.

2.12.9.1 The Effect of Electrolyte Concentration on P Adsorption

In general, phosphate adsorption onto soils has been defined as an inner-sphere complexation (Parfitt, 1978). That is, phosphate ions have an ability to approach the soil colloid surface much more closely than the background electrolyte ions, which are restricted to the outer-sphere of the solid-liquid interface (Yariv and Cross, 1979; He et al., 1997). He et al. (1997) reported that the adsorption of

phosphate depends upon pH and stated that at high pH values greater adsorption was observed for the solutions with greater ionic strength. To explain this mechanism, as mentioned earlier, due to the inner-sphere nature of adsorption, reactions take place via ligand exchange and covalent bonding between metal ions of the solid and the phosphate ions in solution. The absolute value of the surface potential is changed rather than the charge density with a change in ionic strength. At high pH values, a soil surface generally has a high negative charge and the potential in the plane of adsorption is negative. An increase in the concentration of electrolyte in the solution tends to make the potential less negative; therefore the P adsorption is increased. The opposite occurs at the low pH values where the surface is positively charged. There is a positive potential in the plane of adsorption. Increasing in electrolyte concentration decreases P adsorption.

Ryden and Syers (1975), Ryden et al. (1977), Barrow et al. (1980), and Bolan et al. (1986) reported similar results that at lower pH values (between 4 and 5), an increase in the electrolyte concentration may lead to a decrease in P adsorption in soils. However, a converse outcome was found at higher pH values (>4-5), where increasing the ionic strength increased the amount of P adsorbed by soils. He et al. (1997) also advocated that the effect of ionic strength operates on the electrostatic potential in the plane of adsorption, rather than through its effect on surface charge. Increasing ionic strength could either decrease or increase P adsorption. P can be adsorbed when the potential in the plane of adsorption is either positive or negative because of specific reactions with the soil particle surfaces.

Ryden et al. (1977) found that increasing ionic strength decreased P concentration in equilibrium solution during experiments, i.e., increased sorption. The amounts of phosphate adsorbed from a solution containing CaCl_2 (10^{-2} mol/L)

was between 1.5 and 2.5 greater than those sorbed from water. Similar observations have been made by many research workers. Jones and Fox (1977) compared water, 0.001 and 0.01 mol/L CaCl_2 as supporting electrolyte solutions that for a given level of sorbed P, and found that water led to more than twice as much as P remaining in solution than did 0.01 mol/L CaCl_2 . A significant increase in the level of P remaining in solution (low adsorption) was achieved by reducing the ionic strength of the supporting solution. Ryden et al. (1977) also concluded that concentration of the electrolyte and the cation present had a significant effect on the amount of P sorbed by the soil. Similar results were observed for soils by Rajan and Fox (1972) and by Bar-Yosef et al. (1988) in clays (kaolinite and montmorillonite). The largest increase in the amount of P adsorption due to an increase in ionic strength was noticed between the range from 0.2 and 5 dS/m.

Ryden et al. (1977) reported that the ionic strength and cation species of the matrix solution play a critical role in P sorption by soils. An increase in ionic strength decreases the thickness of the diffuse layer, and accordingly reduces the amount of the solution directly influenced by the soil particle surface. If the charge on the surface remains constant, the concentration of anions in the diffuse layer will increase. Parks and de Bruyn (1962) also noted that an increase in ionic strength at constant pH also increases the surface charge, and the absolute amount of counter ions in the solution near the surface.

Helyar et al. (1976a) concluded that there was no significant difference in the amount of P that was absorbed by mineral gibbsite in the presence of Na, K or Mg at different concentrations. This investigation involved equilibration of the mineral gibbsite suspension with the P solution: $\text{Ca}(\text{H}_2\text{PO}_4)_2$ or NaH_2PO_4 . Working at a constant pH of 5.5, it was observed that when the electrolyte concentration was

changed, P adsorption was not affected by Cl salts of Na, K or Mg at any concentration. It was suggested that pH at 5.5 might be a point of zero salt effect on adsorption, that is, the salt concentration had negligible effect on the amount of P sorbed. A similar study was performed by Bolan et al. (1986). It was noted that there is always a point of zero salt effect on adsorption for the mineral or soil, at which concentration of the electrolyte, does not affect the amount of P that is sorbed. Blackmore (2002) showed that there is a slight increase in adsorption of P on pure clays (kaolinite) with increase in ionic strength, but this is generally limited to pH values above the point of zero charge (PZC).

Thus it can be seen that ionic strength is likely to have an effect on the amount of P adsorption on soil with the pH of the soil solution also influencing this process. Many studies have indicated that the point of zero salt effect for various soil ranges from pH 4-5 (Barrow et al., 1980; Barrow, 1984). In this range of pH, ionic strength showed little effect on P adsorption. However, when the pH is increased, an increase in salt concentration is likely to cause an increase in adsorption.

2.12.9.2 The Effect of Cation Species on P Adsorption

It has been reported that specific interactions occur between P and some cations, can lead to an increase in the amount of P adsorbed by soils. Cations may affect on the adsorption of P by the mechanism explained below.

Divalent cations enhance P adsorption relative to monovalent cations. Clays saturated with Ca^{2+} have been found to retain greater amounts of P anions than those saturated with Na^{+} ions (Havlin et al, 1999). This may be explained by the more positive charge at the edge sites of clay minerals, which are accessible to P anions. This effect of Ca^{2+} happens at pH values slightly less than 6.5. In a real soil, Ca-P

minerals would directly precipitate from solution (Havlin et al, 1999). Ryden et al. (1975) and Barrow et al. (1980) also reported similar results - greater adsorption was found in the presence of calcium (Ca^{2+}) than that of sodium (Na^+) for goethite. Barrow et al. (1980) also found that P adsorption in CaCl_2 was greater than in NaCl solutions of equal ionic strength. This may be partly explained due to the greater valency of Ca^{2+} with respect to Na^+ and partly to a specific affinity of calcium ions for the surface. Certain divalent cations increase adsorption, because they can fit into cavities between adsorbed phosphate ions (Clark and Peech, 1960; Helyar et al. 1976b).

Barrow (1984) also examined the adsorption isotherm using NaCl as a background electrolyte instead of using CaCl_2 . He found that adsorption decreased with increasing in pH more rapidly in NaCl compared to CaCl_2 solution. The P adsorption in alkaline and calcareous soils depends on pH. The concentration of HPO_4^{2-} phosphate ion decreases with increasing in pH. Therefore, over the alkaline pH range, the adsorption increases as the pH increases (Pratt and Thorne, 1948). Similar experiments were conducted by Curtin et al. (1992). Soil samples were pre-soaked with CaCl_2 . Similar results were observed. More P was adsorbed when soaked with CaCl_2 than those soaked with NaCl at the equivalent salt concentrations. The amount of P adsorbed by the Na and Cl incubated soil was reduced significantly when the pH in the solutions was increased. This system was strongly pH-dependent. The difference in adsorption was reported as due to changes in the electrostatic potential rather than to the formation of a precipitate or surface complex. Hence, it was suggested that the electrostatic potential decreases more rapidly as soil pH decreased in a Na salt solution than in a Ca salt medium (Barrow, 1984).

Handoyo (1996) also showed that the average pH values of the supernatant solutions of various matrix solutions of the soils were lowest in 1 mol/L NaCl and highest in 0.001 mol/L NaCl and/or water. It was concluded that salinity can affect the P adsorption/ desorption behaviour in soils and sediments. Phosphate sorption by soil and sediment surfaces decreases relatively slowly until pH 7 is reached (Haynes, 1984).

Lehr and Van Wesemael (1952) observed the influence of neutral salts on the solubility of soil P. It was found that the P solubility was depressed in order of $\text{Na} < \text{K} < \text{Mg} < \text{Ca}$. Sandy and loamy soils were more sensitive than river clays and sea clays for P solubility. Humus content reduced the effect of salts as seen by less P fixation in soils with higher humus contents. Contrasting with previous work, there was no correlation between available P and pH. In calcium nitrate solutions, soil P was adsorbed more than in sodium nitrate media. Phosphate ion tends to be attached easier in the presence of high charge ions with high positive charge.

In conclusion, the literature has indicated that effect of increasing the concentration of the electrolyte in soil solution generally leads to an increase in P adsorption. However, the outcome is also dependant upon pH. At low pH values, increasing the concentration of either sodium chloride or calcium chloride salts decrease P adsorption. As the pH is increased, an increase in salt concentration increased adsorption. At higher pH values, with surface predominantly negatively charged, increases in salt concentration make the potential in the plane of adsorption less negative and hence increase adsorption. Therefore, it can be seen that salts influence P retention in soils. The main effects are due to the changes in pH, the medium concentrations and electrolyte.

2.13 P in Plants

In plants, P is a structural component of biochemicals including the nucleic acids, e.g., RNA and DNA. These nucleic acids control the development and heredity processes in plants, so a lack of P can have a serious effect on plant growth and reproduction (McLaren and Cameron, 1996). Phosphorus takes a part in the photosynthesis in plants (Troeh and Thompson, 1993). In plant metabolism, P compounds play a direct role as a carrier of energy and aid in the maintenance of cell colloids and the viscosity of protoplasm. Increased protoplasmic hydration is considered to be connected with the salt tolerance of plants (Ravikovitch and Porath, 1967). Phosphorus is also essential for phytin, which is an important component of seeds (Wolf, 1999). Plants absorb P only as inorganic P ions from the soil solution; therefore, the measurements of inorganic P in plant tissue are made to provide an index of the supply of P in the soil (Black, 1957; Holford, 1997). The average soil solution P concentration is about 0.05 mg/L and varies among soils. The solution P concentration required by most plants varies from 0.003 to 0.3 mg/L depending on crop species and level of production (Havlin et al., 1999). Brady and Weil (1996) noted that a concentration of 0.2 mg P/L in the soil solution is adequate for optimum growth of most crops. **Table 2.7** contains data on the estimated concentration of P in soil solution giving 75 and 95% maximum yield of some crops. A satisfactory supply of P is associated with an improved quality of certain fruit, forage, vegetable, and grain crops and also increased disease resistance (Havlin et al., 1999).

Table 2.7. Estimated concentration of P in soil solution associated with 75 and 95% of maximum yield of selected crops. Source: Fox, Better Crops Plant Food, 64:24 (1982) from Havlin et al., 1999.

Please see print copy for Table 2.7

2.13.1 P Deficiency Symptoms

P is recognised as a limiting nutrient for plants. P is absorbed by plant roots and then distributed to all living cells in the plant especially in the plant's reproductive parts and meristematic tissues where cells are dividing and enlarging (Troeh and Thompson, 1993; Brady and Weil, 1996). Phosphorus is important for pasture establishment, and soil levels of P are critical, especially, during early plant growth stages (Wright et al., 1984). **Figure 2.17** presents the P cycle in a pasture system. As stated above, P is mobile in plants, and as plants mature, most of the P in the plant moves into the seeds and/or fruits (Fertiliser Industry Federation of

Australia, Inc. & CSIRO Australia, 2000). Likewise, when deficiency occurs, P in the older leaves is mobilised and transferred to the newer growing leaves. Therefore, P deficiency is prominent on older leaves.

Deficiency symptoms can be observed from plants with:

- Stunted growth;
- Thin-stemmed plants;
- Spindly growth;
- Dark, bluish green foliage but in severe cases can cause yellowing, senescence of leaves, purple colours of plants in their leaves and stems with tips dying;
- Delayed maturity;
- Sparse flowering;
- Poor seed quality or poor opening of buds; and,
- Reduced root development.

Phosphorus is involved in genetic material and is a component of the cell nucleus. Cells cannot divide if they contain inadequate amounts of P, leading to stunting, delayed maturity and shriveled seeds or light weight seeds with poor viability. A low supply of P obstructs metabolic processes, such as, conversion of sugar into starch and cellulose. The building up of sugar leading to the formation of anthocyanins results in purple spots or streaks in leaves and stems. High chlorophyll contents result when P is deficient, so plants show a dark green colour (Thorne and Peterson, 1954; Troeh and Thompson, 1993; Brady and Weil, 1996; Havlin et al., 1999).



Please see Figure 2.17

Figure 2.17. P in pasture system (McLaren and Cameron, 1996).

2.14 Pasture Species Studied

In grassland systems, there is always a combination of pasture species. This is due to the differences among the species in their response to different levels of soil nutrient supplies and also their variation in relative competitive ability especially with the supply of P. Therefore, the utilisation of P is more effective in grasslands where there is a combination of pasture species. Another reason to have a

combination of grasses and legumes in pasture areas, is the fact that N-fixing symbiosis in legumes provides nitrogen in forms available for use by the grasses.

The pasture species used in combination in Australian grasslands, and some of their characteristics are given below:

2.14.1 Legumes

2.14.1.1 Red Clover (*Trifolium pratense*) Cv. Hamaua

Red clover is a short-lived perennial grass having a significant growth in early summer through autumn under good seasonal rainfall conditions or irrigation (Orchard, 1988). It is easily established. Its morphology includes moderately deep taproot, coarse-stemmed and yellow/purple flowers. **Figure 2.18** shows the morphology of red clover. It grows well on a wide variety of soil types, but on well-drained soils, and is particularly useful as a pioneer species on low fertility soils (Kelso et al., 1990). Red clover is salt sensitive with a salinity threshold of 2 dS/m, and plants will start showing injury beyond this value.



Figure 2.18. Red clover morphology

2.14.1.2 White Clover (*Trifolium repens*) Cv. Osceola

This perennial legume grows well where the average annual rainfall exceeds 800 mm, especially during late spring and early summer. It is suited to a variety of soil types and fertility levels, and even grows on low fertility acid soils. It has shallow roots, which grow from stolon nodes; therefore it is sensitive to dry conditions, and is thus limited to areas with humid summers (Malcolm et al., 1996). Flowers are white or pink. It responds readily to high phosphate rates on low fertility soils. White clover is moderately salt sensitive, and the salinity, which causes injury, is 2-4 dS/m.

2.14.1.3 Birdsfoot trefoil (*Lotus corniculatus*) Cv. Goldie

This legume is suited to clay soils and to areas with wet or acid conditions. It has a relatively slow growth rate and small seed size. It has deep fibrous root system. Birdsfoot trefoil should be treated before planting with Rhizobium bacteria that fix atmospheric nitrogen, reducing the use of nitrogen fertilisers. It grows well in early spring or late summer, but during early spring it gives best growth due to suitable soil moisture for germination and seedling development. It is tolerant to low fertility, drought, and low soil pH. However, the maximum forage growth occurs on fertile soils with pH between 6.0 and 6.2. Moderate application of P and sulfur at planting will provide good growth (The American Forage and Grassland Council, 1995). Birdsfoot trefoil is moderately salt tolerant, the salinity causing damage is from 4-6 dS/m. This species needs inoculation because it has an ability to fix nitrogen from the atmosphere and this will reduce the nitrogen fertiliser application.

2.14.2 Grasses

2.14.2.1 Perennial ryegrass (*Lolium perenne*) Cv. Impact

Perennial ryegrass, also called English ryegrass, is a cool-season perennial bunchgrass (see **Figure 2.19**). This is salt tolerant and suitable to most soil types. It also tolerates both acidic and alkaline conditions with a pH range of 5.1 to 8.4. It responds well to high fertility conditions. It is fast growing in autumn, winter and spring producing a significant amount of dry matter. This grass is easily established where annual rainfall exceeds 600 mm. During drought and in hot summers, growth rates are reduced. It is susceptible to scarab attack and rust. Ryegrass is moderately salt tolerant, the salinity causing damage is from 4-6 dS/m (Wolf, 1999).

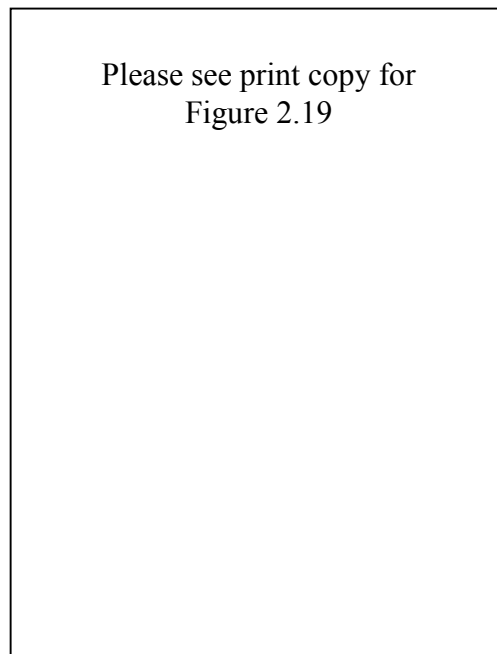


Figure 2.19. Morphology of ryegrass (Hannaway et al., 1999).

2.14.2.2 Orchard grass (Cocksfoot) (*Dactylis glomeratum*) Cv. Currie

This perennial grass is a bunchgrass (Duncan, 1978). It can grow on less fertile soils containing moderate levels of aluminium. It has a deep rooting system

and is able to persist in a dormant state through short summer droughts. Orchard grass is easy to establish and regenerates from seeds. It grows well during autumn, summer and spring. However, orchard grass requires a well-drained soil and persists better on sandy soils and is tolerant to acidic soils (Malcolm et al., 1996). It is less susceptible than ryegrass to scarab attack. Orchard grass is moderately salt sensitive; the salinity has impact at 4-6 dS/m (Wolf, 1999). Data on salt tolerance shows that grasses have a greater ability to persist at high salinity levels than the legumes (see **Table 2.8**).

Table 2.8. Salinity threshold (EC) and P solution concentration level in soil solution (Maas and Hoffman, 1977; Peverill et al., 1985).

Please see print copy for Table 2.8

Note: NA = Data is not available

2.15 Summary of Literature Review

Soil salinity is one of the World's most serious environmental problems. It threatens land areas worldwide and causes land degradation consequently, problems such as decrease in agricultural lands, biodiversity loss, economic losses, etc.

Salinity is considered as a problem when concentrations of sodium chloride, sodium carbonate, sodium sulphate or salts of magnesium are present in excess amount in soils. There are 2 types of soil salinity: Primary salinity (natural) and Secondary salinity, which is caused by human activities and can be categorised into 2 types; irrigation salinity and dryland salinity. Causes of secondary salinity include land development, forest clearing and the change of landscapes. These lead to rises in groundwater tables, subsequently, salts accumulate in the soils when the water evaporates and form salt affected soils.

There are 3 types of salt-affected soils; saline, sodic and saline alkaline sodic soils, classified by using EC, pH, and ESP. Salinity affects soil physical and chemical properties, and, as a result, plants grown on those soils. Salinity affects plants in many different ways, but mainly through direct effects of salts in preventing water uptake, direct chemical effects of salts in disturbing plant nutrition and metabolism, and the indirect effects of salts in altering soil structure, permeability, and aeration.

Plant injury visible symptoms caused by salinity include stunting, delayed maturity and purple spots. Essential nutrients are also limited in soils where salts are present in substantial quantities.

Most arable lands in Australia are used for crops and pastures and the national economy is significantly reliant on dairy products. Consequently, fertiliser application is necessary in pasture and cropped lands to improve yields. P is an

element of major importance as it is considered as a macronutrient and its use is second only to nitrogen in significance for crop production. However, some areas have been over fertilised causing eutrophication in waters by run off. Therefore, optimum P application must be carefully considered, especially where salts affect land. There are inconsistent outcomes reported in the literature on the use of P fertilisers in salt-affected soils. Reported studies have shown positive, negative and no effects of P fertilisation on crops growing in salt-affected soils. The contradictory results may arise from different sources, e.g., the ways researchers carrying their experiments, such as soil or sand pot experiments in greenhouse, sand culture, nutrient solution culture, or even in field experiments, as well as different environmental conditions such as seasonal change, humidity, climate or temperature conditions. These all are likely to affect the results of the studies.

P behaves differently in different soil types and when soils are affected by salinity, P has been shown to be less available. Generally, total P in normal soil ranges from 0.02-0.05% depending on parent material, the extent of weathering and leaching. Plants absorb P in 2 forms - H_2PO_4^- or HPO_4^{2-} ions and these two ions occur preferentially in soils with different ranges of pH.

P fixation is the major mechanism controlling the behaviour of P in soils. The phenomenon through which P is removed from solution by soil or soil constituent called 'sorption'. Adsorption occurs by physical sorption, chemisorption and surface precipitation. Factors that affect the availability of P in soils (factors that influence P sorption) include oxyhydroxide content, nature and quantity of clay, pH, extent of P saturation, organic matter, time, temperature, moisture and effects of salts and ionic strength. The latter factors, salts and ionic strength are of interest in salt-affected soils, where P fertiliser application rates have to be determined for reasonable uptake

by plants. Increasing electrolyte or ionic strength in soil solution often increases P adsorption, but the outcomes also depend on pH.

In this current research, the aims were to examine the effects of P application on salinity impacts on pasture plants. The interactions between salinity and P were also studied by a series of pot experiments and by laboratory studies.

CHAPTER 3

EXPERIMENTAL MATERIALS AND METHODS

3.1 Introduction

The experimental work was conducted in 4 parts, each part being developed from the results of earlier experiments.

- 1) The electrical conductivity produced by using NaCl salts was measured to give the data necessary for planning the salinity-P interaction experiments.
- 2) P sorption isotherms were examined in the laboratory to evaluate the interaction between salinity and P adsorption, and hence, possible effects on plant uptake of P. Phosphorus adsorption isotherms were determined for 3 soils with different characteristics, with and without NaCl addition, to ascertain the effects of salinity on P adsorption.
- 3) Preliminary pot trial experiments were undertaken to determine the optimum P for each pasture species under the experimental conditions being used, in the absence of salinity stress.
- 4) Sand culture and pot experiment techniques were used to maintain more uniform salinity around the roots for salinity-P treatments (Rowell, 1994) and also in P treatments to avoid the influence of P sorption and other interactions on plant growth response.

Pot experiments were conducted at varying P concentrations with variable salinity to assess the interactions of P and salinity in pasture species growth.

Plant tissue analysis data (above ground materials) was obtained to give direct indications of plant uptake of P and other elements in the presence of salt.

Information on soils studied, instrumental techniques (e.g., pH, salinity, P measurement), source of deionised water and plant tissue harvesting, experimental design, sand preparation, pasture species for the pot experiments, greenhouse layout, water regime and detailed experimental methods for completion of pot experiments are given below.

3.2 Soils Studied

3.2.1 Introduction

This section presents information on the soils used, soil sampling, preparation and the results of the analysis of various properties.

3.2.2 The Soils

Three soils were chosen from 3 sites of New South Wales; 2 sites from the Illawarra region (JBU1, DP1, and DP2) and 1 site from the Shoalhaven region (TG1). These 3 soils had different soil physical and chemical properties, mineralogy and the sites were located in different geological zones. Detailed information about soil samples, locations, soil profiles, mineralogy, and soil properties are given in the following paragraphs and in **Appendix 3**.

3.2.3 Soil Profile Descriptions

Soil profile descriptions are given in **Appendix 3**. Soils mineralogy is presented in **Appendix 3 (Tables A6)**.

3.2.4 Soil Sample Preparation

After collection, soils were air dried for approximately 1 week. Roots, debris and other organisms were removed and the soils were ground and sieved to <250 μm for organic carbon determination and passed a <2 mm screen for other chemical analysis. Soils were stored in plastic containers until needed. Data on the soils was

available from previous studies: TG1- Green (1997) and Quinane (1997); JBU1- Pou Va Ku (1995), Truong (1997), Handoyo (1996); and DP1- Milham (2002). Soil mineralogy and the analyses including pH in water, moisture content, exchangeable cations, organic carbon, and clay content for soil properties are tabulated in **Appendix 3 (Table A7)**. Phosphorus adsorption analysis information is presented in **Section 3.5**. DP2 soil was used for some pot experiments.

3.3 Instrumental Techniques

3.3.1 pH

The pH of sand and soils used in the pot experiments was determined by using pre-calibrated pH glass electrode meter- Crison Micro pH 2001. The pH was normally measured in water using a soil to water ratio of 1:2.5.

3.3.2 Salinity

Electrical conductivity was measured by using an Orion Model 160 conductivity meter, pre-calibrated with KCl (0.1 mol/L)

3.3.3 P Concentration in Solution

Phosphorus concentrations were determined using the Murphy and Riley (1962) technique with ascorbic acid as the reducing agent. Absorption was measured using a UNICAM UV-1201 spectrophotometer after allowing 30 minutes for colour development.

3.3.4 Weighing

Soils, plants and chemicals were weighed by using digital scientific balance that was regularly calibrated.

3.3.5 Deionised water

Deionised water was prepared using a Millipore reverse osmosis system. Water purification system specifications were 5-10 $\mu\text{S}/\text{cm}$, and this has been checked regularly.

3.3.6 Harvesting of Plants from Pot Experiments

Plants were harvested by removing the above ground parts from the pots and cleaned with deionised water to remove excess sand/soil. Fresh weight was recorded immediately afterwards. Yields and mineral element concentrations in plant tissue are presented on the dry weight basis. Dried weight was measured after oven drying at 70 °C for 24 hours. After weighing, dried samples were ground and analysed for tissue content of selected elements.

3.4 Salt Concentrations and Electrical Conductivity (EC)

The relationship between EC and salt concentrations in the solution was established using standard solutions. Sodium chloride (35 g) was dissolved in distilled water (1 L) and the electrical conductivity measured with a pre-calibrated conductivity meter. The solution was accurately diluted using deionised water and the electrical conductivity of a series of solutions with different levels of salt concentrations was measured. The results are presented in **Figure 3.1**. The data obtained were used in preparation of solutions having particular conductivities in later experiments. A note of EC units is given in **Appendix 1**.

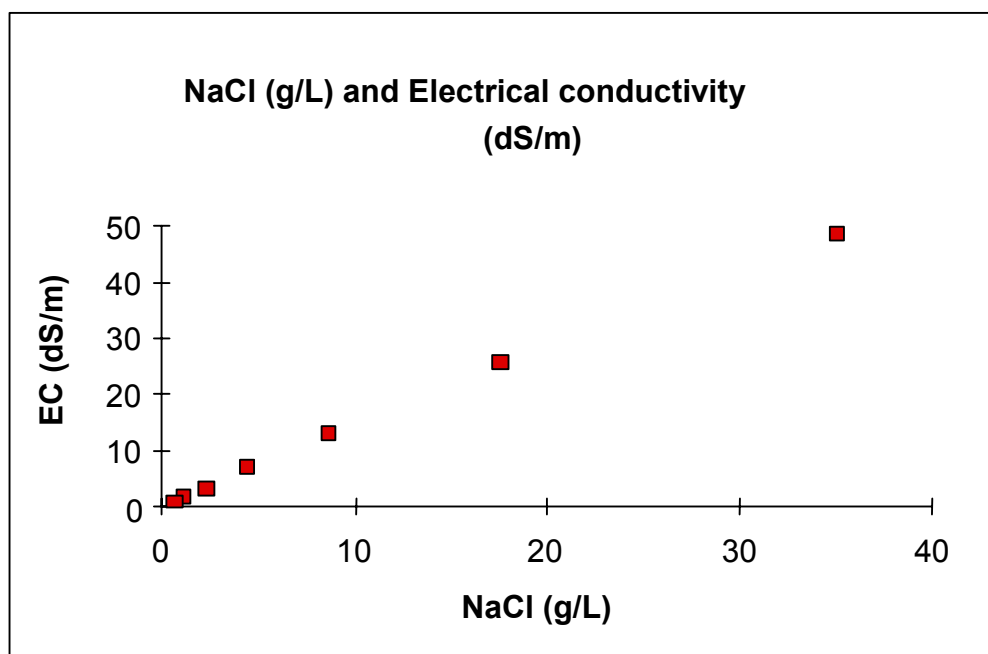


Figure 3.1. Electrical conductivity (dS/m) of salt solutions plotted against concentration of NaCl (g/L).

3.5 P Adsorption Analysis

As noted in **Section 3.2**, three soils (DP1, TG1 and JBU1) were collected from different locations.

DP1 was considered a saline soil and was collected from near the Duck Pond at the Elizabeth Macarthur Agricultural Institute (EMAI), Camden, NSW. TG1 samples were collected from a tea tree experimental site at Ulladulla, NSW. JBU1 soil was collected from Saddleback Mountain Road, South West of Kiama, NSW. TG1 was considered to have low P adsorption capacity, while JBU1 soil was expected to have a high P adsorption capacity. DP1 was expected to have an intermediate value.

3.5.1 P Adsorption Isotherm Procedure

A P sorption isotherm describes the equilibrium relationship between the quantity of inorganic P sorbed by the soil and the changing concentration of P remaining in the ambient solution (Holford, 1989) - see **Section 2.11**. The procedure used in this study was adopted and modified from the Australian Soil and Land Survey Handbook (Rayment and Higginson (1992), Murphy and Riley (1962), and Dandy and Morrison (1978)). There are 3 processes involved in this procedure:

- 1) Preparation of calibration curve for determining concentrations of P in solutions;
- 2) Determination of soil adsorption isotherm; and,
- 3) Interpretation of the experimental data.

Calibration Curve

Clean and labelled volumetric flasks (5 x 50 mL) were added accurately known volumes of standard KH_2PO_4 (0.516 g/L, giving 0.1176 mgP/mL) successively (0, 0.1, 0.2, 0.4 and 0.5 mL). 5 mL of colour reagent was added to each flask and made up to 50 mL with deionised water, mixed thoroughly and 30 minutes allowed for colour development. The solution absorbance was measured at 882 nm using a spectrophotometer. The solution with zero added P solution was used as a blank. The values of absorbance were plotted against mg P in 50 mL of the solution. Calibration curves were prepared on each day that P analyses were being performed. The slope of the curve varied by <5% during the study period.

Soil P Adsorption Isotherm Determination

Soil (2 g, air-dried, < 2 mm) was weighed into 80 mL centrifuge tubes. KH_2PO_4 solution (about 0.1 mgP/mL, accurately determined) was added in varying

amount and 5 mL of CaCl_2 (0.1 mol/L) was added to each tube; the volumes were then made up to 50 mL with distilled water. This gave a CaCl_2 concentration of 0.01 mol/L. The supernatant P concentration (c) was measured after an equilibrium period of 16 to 20 hours in end-over-end shaking (15-30 rpm), at room temperature. The measurement was performed by taking a known volume of solution, after centrifugation and filtration, placing it into 50 mL volumetric flask, adding 5 mL of colour reagent and making up to 50 mL with distilled water. The solution was mixed carefully and after allowing 30 minutes for colour development, the absorbance at 882 nm was measured by using the spectrophotometer.

Interpretation of the Experimental Data

The P calibration curve was used to estimate the amount of P in each diluted solution. The P concentration in solution at the equilibrium was obtained by multiplying by a factor 50/volume used for analysis. Sorbed P was inferred from the difference between the concentrations of solution P added in the initial solution and the concentration of P in the solution at equilibrium. The amount of adsorbed (mg) per gram of soil (x) was obtained by dividing the weight adsorbed by the weight of soil used. The equilibrium P concentration in solution in mg/1000 mL was obtained by multiplying the total mg of P in a 50 mL reaction solution by 20. The P sorption curve for a given soil was constructed by plotting sorbed P (per g soil, x) against equilibrium P concentration (mg/L, c). Maximum P adsorbed was obtained by the Langmuir Equation (**Section 2.11**).

3.5.2 Salinity Effects on P Adsorption

Salinity effects on P adsorption isotherms were investigated using 3 separate procedures.

3.5.2.1 Direct addition of salt to P sorption solutions

In this procedure, dried soil samples were shaken with P solutions containing NaCl at different concentrations: 0.04, 0.08 and 0.12 mol/L NaCl. These concentrations were prepared using 2 mol/L NaCl (the volume used was 1, 2 and 3 mL of 2 mol/L NaCl respectively in 50 mL reaction solution). The P adsorption isotherm was completed in the same way as in **Section 3.5.1** (with CaCl_2 present at 0.01 mol/L).

3.5.2.2 Incubation of soil with salt at field capacity, followed by reaction with added P

Dried soils (weight) were mixed with NaCl salt (weights designed to give appropriate salt solution concentrations) in later P sorption studies, and water was added to the field capacity to produce artificial saline soils at different salt concentrations. The mixtures were thoroughly mixed, and after storage at room temperature for 2 weeks, the soils were dried. Phosphorus adsorption isotherms were then measured for the salt incubated soils (with CaCl_2 added at 0.01 mol/L). Soil was equilibrated in a 1:20 soil to solution as in **Section 3.5.1**.

3.5.2.3 Incubation of soil with saline solutions followed by reaction with added P

The third procedure was used to examine the effects of salt on P adsorption by prolonging the duration (72 hours) of NaCl solution contact with 2 soils (DP1 and JBU1) before adding the P solution for P adsorption analysis. NaCl solution at 2 different concentrations (0.04 and 0.12 mol/L NaCl) was shaken with the soil (soil:

solution ratio 1:20) for 2 different periods of time (16 and 72 hours), following by P adsorption analysis.

The pH of the soil aliquots (before performing P adsorption analysis) was recorded to observe the influence of pH on P adsorption by using pH meter which was pre-calibrated by buffer solutions pH at 4 and 7. However, the pH values showed no significant difference in each treatment.

3.6 Sand Preparation

River sand was obtained from a commercial sand provider. The sand was cleaned with tap water until the water became clear and then sieved through 500 μm sieve. Clean sand was soaked with 10% HCl for 50 hours before cleaning and rinsing with distilled water until all the acid was removed as indicated by measuring the pH. Dry sand was obtained by drying in an oven at 35-40°C. The acid washed sand was kept in covered containers until needed.

3.7 Sand Electrical Conductivity, pH and Water Holding Capacity

The electrical conductivity and pH of the acid washed sand were measured by using a calibrated electrical conductivity meter and pH meter. Sand (10 g) was added into distilled water (25 mL) and shaken before testing.

The water holding capacity of the sand was determined (in quadruplicate) by placing 500 g of sand in the testing pot (size = 8x14x5 cm^3) lined with filter paper. The sand pot was soaked by standing in water overnight. After taking the pot out of the water, the sand was left to drain for 2 days before measuring the weight again. The final weight obtained, minus the initial weight of the sand, gave the water holding capacity of the sand.

3.8 Pasture Seed Germination Trials

Pasture seeds were obtained from Elizabeth Macarthur Institute (EMAI), Camden, NSW. Large samples of seeds were obtained to avoid changing sources during the experiments. Seeds were germinated in the laboratory at room temperature to assess the seed quality and percentage germination. Triplicate experiments where known numbers of seeds of each species sown in sand filled petri dishes with moist sand were set up. The sand was kept moist and the seeds were checked daily to determine the numbers germinated, and hence calculation of germination rate. The effect of salt on germination was carried out with identical experiments except that salt was added to give various concentrations at concentrations of 0, 2, 4, 8 and 12 dS/m (Section 3.4).

3.9 Greenhouse

The temperature and humidity in the greenhouse varied with the climate. During the summer, the top was covered with shade cloth to reduce the heat inside but during the winter the cloth was removed to allow the sunlight penetration because of the slower growth during winter. Pots were placed on the benches above the ground in a randomised pattern. Pot locations were frequently changed to ensure all plants experienced daily similar environmental conditions, in order to prevent positional effects.

3.10 Pot Experiments

Pasture species were grown to maturity in sand and soil culture experiments to study the interactive effects of P and salinity.

8x14x5 cm³ rectangular plastic pots were used in the experiments. For the sand culture experiments, pots contained 500 g of acid washed sand. In the saline soil experiment, pots were filled with 350 g of DP2 soil. Seeds were sown in pots without drainage in the greenhouse (mean temperature varied and depended on climates, in winter temperature ranged between 15±8 °C and in summer 30±8°C). During the growing period, water was applied daily to bring the water content up to 95% water holding capacity of sand/soil. Regarding water capacity, sand/soil lost water about 30% daily in hot weather, but, during cooler periods less than 15% of water was lost daily. So during the experiments, pots were maintained at this level by daily watering after weighting, based on the initial weights. In the sand culture experiments, seeds were germinated in the pots and thinned to 10 plants each pot after their good establishment. P was added afterwards (about 2 weeks). In salinity – P treatments, NaCl solution and P were treated by the same approach. This allowed plants to establish without salinity. Half strength Hoaglands nutrient solution composed of micro and macronutrients except for P (see **Appendix 2, 2.1**) was added weekly (Cerde et al., 1977). The duration of the experiments was normally for 12 weeks after adding the P and salt. For the saline soil (DP2) study, P was managed in the same manner as in the sand culture experiments. However, a thin layer of sand was placed on the top of the soil to assist in germination. All pots were periodically rotated.

All cultures were harvested after 12 weeks (unless otherwise indicated), and the plant materials handled as described in **Section 3.3.6**.

After harvest the above ground parts of plants, for most of experiments, the pots were carefully examined. Sand and soil were separated top part from lower part for analysis to observe if there was nutrients/salt migration. Plant root distribution was also examined in the pots.

3.10.1 Determination of Optimal P Addition Rates for Pasture Species (High Range of P)

Pot experiments were conducted in the greenhouse in summer for 12 weeks using 5 pasture species: 3 legumes (red clover, white clover and birdsfoot trefoil), 2 grasses (orchard grass and ryegrass) with 6 levels of P added as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ solution (0, 25, 50, 100, 200 and 800 ppm) (see **Appendix 2, 2.2.1**) to determine the optimal P required under the experimental conditions being used for each species. With 3 replications, 90 pots were used in the experiment. Twenty seeds of each species were sown in 500 g of sand and seeds were allowed to germinate in a week. After germination and good establishment, pots were treated as described above. Growth aspect with regard to plant physiology was observed and recorded daily. In this experiment, white clover produced very small biomass, therefore it was omitted from the later experiments.

3.10.1.1 The Optimal P for Pasture Species Using Low P Concentrations

Based on the results from the first optimal P experiment (Method in **Section 3.10.1** and discussed in **Section 4.5**), 2 sets of pot experiments were conducted in the greenhouse to confirm the results of the above experiment.

The first set of experiment was conducted in late summer, the experiment involved growth for 12 weeks of 4 pasture species: 2 legumes (red clover, and birdsfoot trefoil), 2 grasses (orchard grass and ryegrass), however with lower levels

of P added as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ solution (0, 0.01, 0.1, 0.5, 1.0, 5.0 and 25 ppm (see **Appendix 2, 2.2.2**)). There were 4 replications, thus the entire study involved 112 pots. In this experiment, pots were watered and added nutrient solution via the surface of the sand. After 12 weeks of growth, plants were harvested. Fresh and dried weights were recorded as before by using the above ground parts.

As mentioned previously, there were 2 sets of experiments involving low range of P, the first set of the experiment produced some unexpected results (see **Section 4.5**), and therefore the following second set of the experiment with the same low P concentrations was carried out after in early autumn. The difference between the 2 sets of experiments was the watering method. The first set pots were watered at the surface, whereas the second one, pots were added water through syringes. The experimental design was identical to the previous one except a small plastic tube was inserted in the middle attached to the syringe. Water and nutrient solution were then added through the syringes so that they entered the middle of the pot (see **Figure 3.2**). After experiment was terminated, plants were treated as above. From the growth data, the optimal P rate was determined and used in later experiments to examine the interaction between salinity and P. Plant tissue elemental composition was determined.

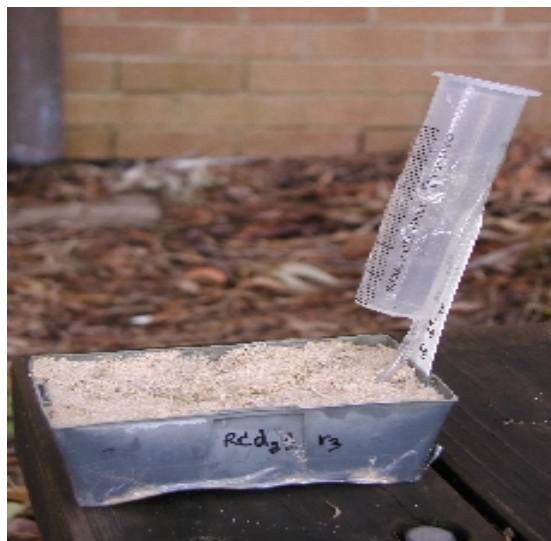


Figure 3.2. Pot was inserted with syringe attached with the tube.

3.10.2 The Effect of Salinity at Optimal P in Ryegrass

This experiment was established to show the effect of salinity on ryegrass yield where P was applied at the optimum level. The experiment was carried in the greenhouse for 12 weeks in sand culture, with varying salinity levels; 0, 2, 4, 8 and 12 dS/m as NaCl. Phosphorus was applied as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at the near-optimum P of 25 mg/L (obtained from previous experiments). There were 4 replications. Therefore, 20 pots were included in this experiment. Base nutrient and water were added as in previous experiments. Ryegrass seeds were sown and thinned to 20 plants after 2 weeks then salinity and P solution were applied after the establishment. Plants were harvest twice; half the pots were harvested after 7 weeks and the other half after 12 weeks. Wet and dry weights of plant material were recorded. Plant materials were analysed for mineral compositions.

3.10.3 The Effect of Varying P at Constant Salinity Levels on Pasture Species-Pot Experiment

Pot experiments were carried in the greenhouse during summer for 12 weeks using 4 pasture species: 2 legumes (red clover and birdsfoot trefoil), 2 grasses (orchard grass and ryegrass) with 5 levels of P at 2 levels of salinity for each species. P solution was applied as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ giving 3, 10, 17, 25 and 35 ppm (see **Appendix 2, 2.2.3** for details) and cultures were salinised to 0 (control) and 4 dS/m by NaCl solution. There were 2 replications for the control and 3 replications for the treatment group. Thus, 2 levels of salinity and 5 levels of P were combined in 2x5 factorial designs. Known numbers of seeds of each species were sown in each pot. After good establishment and thinning, P solution and salinity were imposed. All pots were treated in the same manner as in previous experiments. Conductivity (salt concentration) was maintained uniform throughout the pot. During the experiment, plant morphology such as colour and growth descriptors was observed to assess the effect of salinity on growth. After 12 weeks, the above ground plants materials were collected. Fresh and dried weights were measured. Plant materials were analysed for tissue elements.

3.10.4 Plant Growth in a Naturally Saline Soil with Varying P at Constant Salinity (DP2 Soil)

Pot experiments were conducted in the greenhouse during winter to examine whether similar results are obtained for a real saline soil as with saline induced sand, i.e, does P assist plants overcome effects of salinity or not. The experiment was carried during winter for 12 weeks using 2 pasture species (red clover, and ryegrass) as representatives of legumes and grasses respectively. The 2 selected species were

used because they produced the best yields in the previous experiments. The natural saline soil (DP2) collected from EMAI with the original electrical conductivity ($EC_{1:5}$) = 0.85 dS/m (EC_{Se} = 5.95 dS/m, calculated from % of clay content, DP2 contained medium clay, therefore ratio of 7 was multiplied to 0.85 giving 5.95 dS/m as EC_{Se} , see **Appendix 1** for conversion) was used in the experiment. A soil P adsorption isotherm was prepared and the P maximum adsorption was calculated to determine the levels of P added in each pot to produce 7 different concentrations of P. **Figure 3.3** shows the P adsorption isotherm for DP2 soil. P was imposed as KH_2PO_4 at 0 ppm (P0), 0.1 x P maximum adsorption (P1), 0.25 x P maximum adsorption (P2), 0.35 x P maximum adsorption (P3), 0.5 x P maximum adsorption (P4), 0.7 x P maximum adsorption (P5), and P at the maximum adsorption (P6). The maximum P adsorption value was 0.31 mg/ g dry soil, thus, P was added at 0, 0.031, 0.078, 0.109, 0.155, 0.217 and 0.31 mg P/ g dry soil were added for P0, P1, P2, P3, P4, P5, and P6 respectively. There were 3 replications in the experiment; therefore, there were 42 pots involved in the whole experiment.

Known numbers of seeds of each species were sown in each pot containing 350 g of soil with a thin layer of sand on the surface to assist in germination. Seeds were allowed to germinate and establish before thinning to 10 plants each pot. Phosphorus solution was applied as KH_2PO_4 at the concentrations noted above (see **Appendix 2, 2.2.4**). Half strength Hoaglands nutrient solution was also added at weekly intervals. The plants were watered daily using deionised water based on the soil field capacity and initial pot weights. There was no drainage from the pots during the entire course of the experiment. Plant morphology was observed regularly, i.e., colour and growth description. After 12 weeks, above ground plants materials were harvested. Fresh and dried weights were recorded. Plant materials were

analysed for tissue mineral contents. Soils used in the experiment were analysed after the experiment was terminated (for comparison with initial properties).

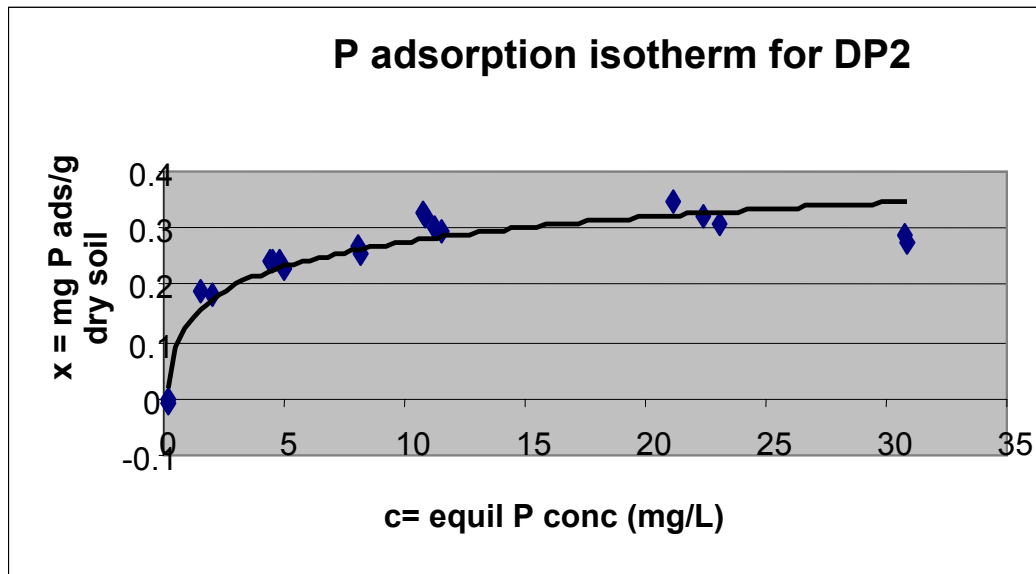


Figure 3.3. P adsorption isotherm for DP2 soil indicated the maximum adsorption at 0.31 mgP / g dry soil.

3.11 Plant Tissue Material Analysis

As mentioned in **Section 2.6.1**, mineral analysis in plant tissues can be used to examine available nutrients in plants.

In this present work, above ground plant materials were dried and ground for analysis. Chemical analysis was conducted on composite plant samples for each treatment from the combined replicates. The analytical procedure used was acid digestion and measurement in Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). The analyses were carried at the Waite Analytical Service, Plant Science Department, Waite Institute, South Australia.

Chloride ion in plant tissue was determined by using a Haake-Buchler Chloridometer. The analyses were conducted at the Analytical Crop Management Laboratory at Loxton, South Australia.

Reference materials were included with the experimental samples. Data on replicates and reference materials showed good quality agreement was in operation. Analytical data for reference plant are presented in **Tables 3.1** and **3.2**.

Table 3.1. Analytical data for reference plant tissue sample (NIST standard reference material, 1515 apple leaves).

Please see print copy for Table 3.1

Table 3.2. Analytical data (mg/kg) for reference plant tissue sample (NIST standard reference material, 1515 apple leaves), (Continued).

Please see print copy for Table 3.2

Note : NA = Not available

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the experimental work carried out, together with discussion of these results. The results include assessment of the properties of sand used for the pot experiments, data on the soils used in the adsorption experiments, P adsorption experiment results and the outcomes of the pot experiments. The pot experiments include assessment of optimum P conditions for the pasture species under controlled experimental conditions. The experiments varied P and salinity conditions, in an attempt to determine possible interactions between these parameters in influencing pasture species growth.

4.2 Salinity Effects on Soil P Adsorption

P sorption isotherms are obtained by plotting the equilibrium relationship between the quantity of inorganic P sorbed by the soils and the changing concentration of P remaining in the ambient solution. In this respect, the results of adsorption isotherm studies can be related to the prediction of P availability in soils.

As mentioned in **Section 3.5.2**, P adsorption isotherms for 3 soils were determined by 3 separate procedures. The following paragraphs explain the results of the study. The treatments with no salt were used as control, except in DP1 soil where the control contained some amounts of salt in nature.

The adsorption isotherm results for 3 soils in the absence of salt are presented in **Figures 4.1, 4.2 and 4.3** for DP1, JBU1 and TG1 soils respectively. The 3 soils showed typical P isotherm patterns, as they rose sharply at low P concentrations, and then became convex to the Y- axis. At high P concentrations, the isotherms became

parallel to the X- axis due to P saturation. The 3 soils sorbed different quantities of P although the general shapes of the isotherms were similar. From the curves, the TG1 soil showed the lowest P adsorption, while the JBU1 soil had the highest P adsorption. DP1 soil (saline soil) showed a P adsorption isotherm intermediate between the other 2 soils.

The adsorption isotherms in semi-logarithmic form with amount of P sorbed plotted against $\log c$ equilibrium P concentrations are shown in **Figure 4.4**. This facilitates comparison of the isotherms of the above data, revealing that the level of adsorption was in the order of JBU1 (P max calculated at 1.355 mg P/g soil) > DP1 (P max = 0.647 mg P/g soil) > TG1 (P max = 0.104 mg P/g soil). The main reasons for the differences between the soils, in terms of sorption, are particle size distribution and mineralogy. High P retention in the JBU1 soil was due to the high clay content (65% clay), while the TG1 soil contained a high content of sand and the clay content was only 3%. DP1 soil showed intermediate value of clay content between the 2 soils (45% clay). The retention of phosphate is greatest in clays (fine particles) due to surface area effects (Wild, 1950; Sharpley, 2000). Larger surface areas have a greater tendency to retain phosphate and the retention decreases as the particle size increases. Similar observations were found in Alabama soils where phosphate adsorption was significantly related with clay content but was not related to other soil properties (Senwo et al., 2003). In this present study, JBU1 soil was found to contain 30-50% oxyhydroxides. As discussed earlier, the high clay content together with a high amount of oxyhydroxides would be expected to lead to high P adsorption. Clay mineral contributions to P adsorption relate to specific area of Fe and Al oxyhydroxides (Juo and Fox, 1977). Holford (1989) also indicated that oxyhydroxides have a high capacity to adsorb large amounts of P from solution,

therefore, are associated to high phosphate sorption in soils. Havlin et al. (1999) also supported the statement that the less crystalline or the more amorphous the oxyhydroxides in soils, the larger their P fixation capacity because of their greater surface areas.

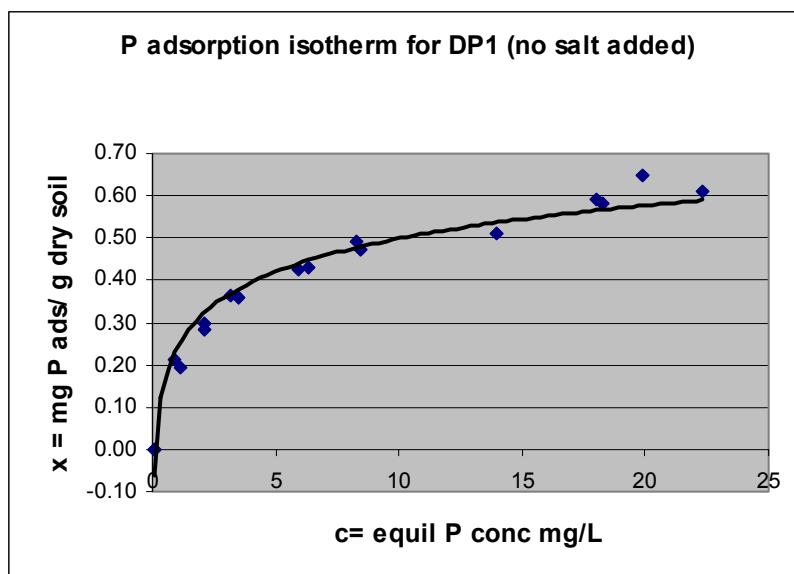


Figure 4.1. P adsorption isotherm for DP1 (control, no salt added).

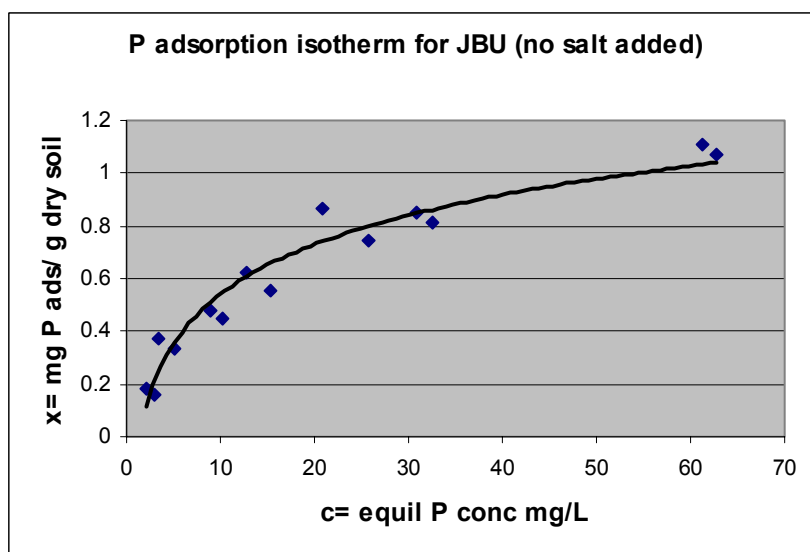


Figure 4.2. P adsorption isotherm for JBU1 (control, no salt added).

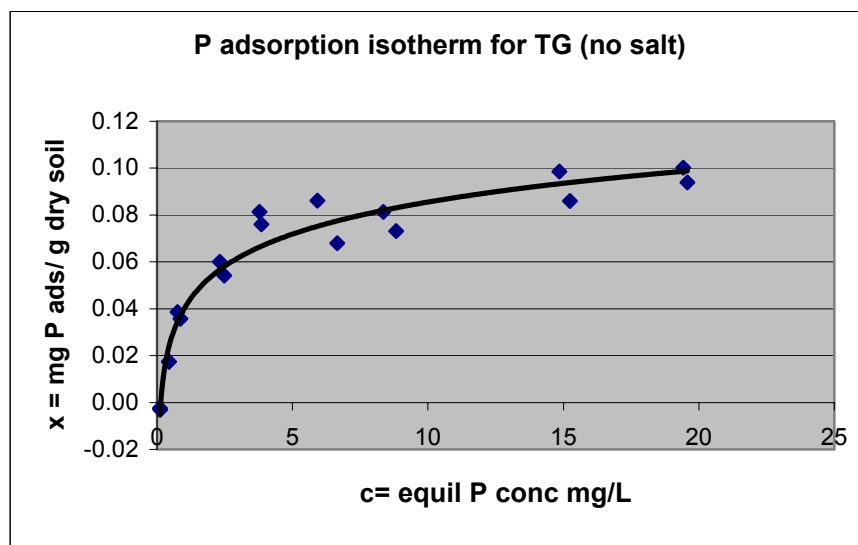


Figure 4.3. P adsorption isotherm for TG1 (control, no salt).

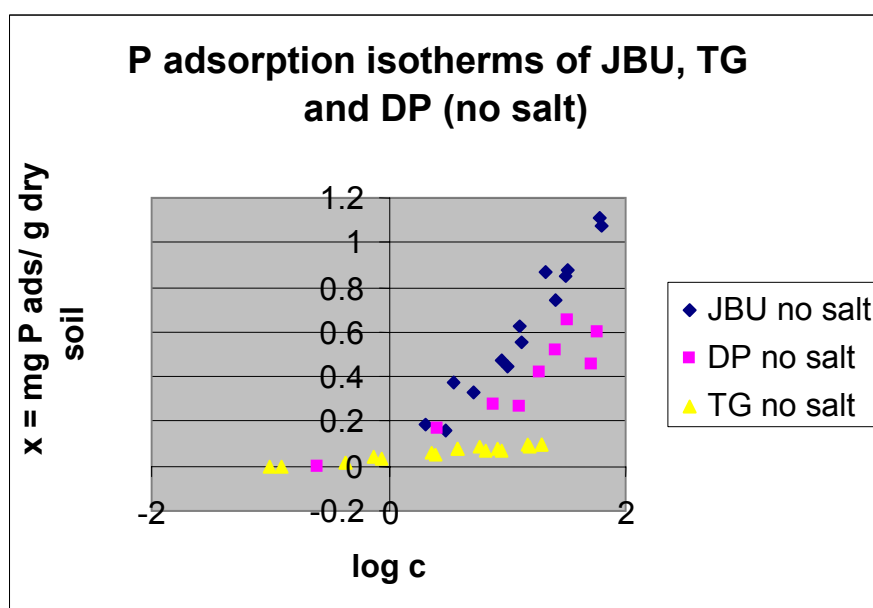


Figure 4.4. P adsorption isotherms plotting between P sorbed (mg/ g dry soil) and log c for 3 soils without salt addition (control).

P adsorption isotherms for soils with the addition of salt were analysed using 3 different methods as described in **Sections 3.5.2.1, 3.5.2.2 and 3.5.2.3**. The first procedure was the incubation of soils with salt at field capacity prior to reaction with added P, the second one was the direct addition of salt to P sorption solutions and the

third involved prolonging the duration of NaCl solution contact with 2 soils (DP1 and JBU1) before adding the P solution for P adsorption analysis. The results of the adsorption studies were as follows.

P adsorption isotherms for soils (semi-log plots) where soils were incubated with salt at field capacity prior to reaction with added P are presented in **Figures 4.5, 4.6** and **4.7** for DP1, TG1 and JBU1 soils respectively. The P isotherms varied among soils. Comparison of the isotherms for a soil when different levels of salt were added showed insignificant change of the P isotherms for a soil with increasing amounts of salt added. This was especially true for TG1 and JBU1 soils. However, there were marked differences in P sorbed with salt present when comparing the P adsorption isotherms between no added salt treatments (control) and salt addition incubated soil treatments (see later discussion).

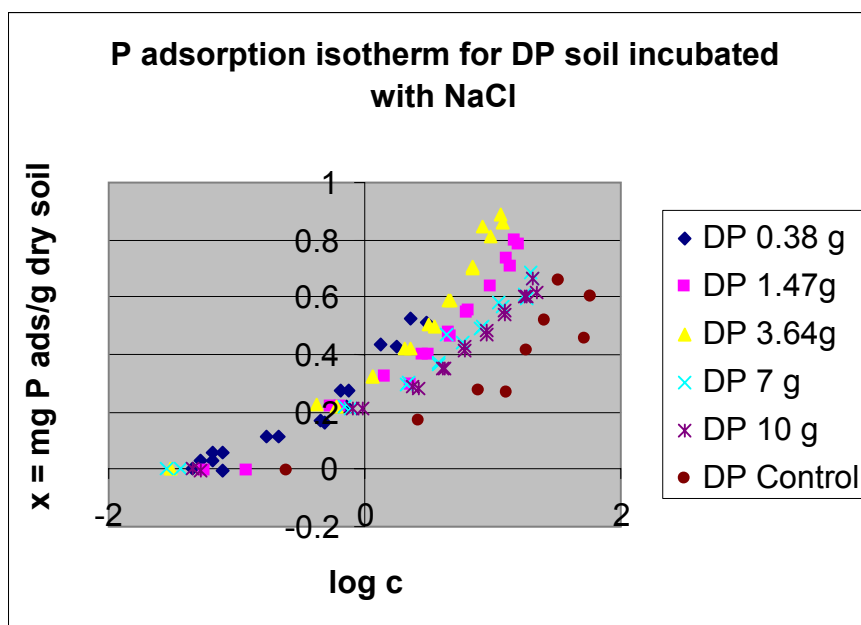


Figure 4.5. P adsorption isotherms for DP1 soil after incubation with NaCl salt (Control- no added salt, 0.38 g, 1.47 g, 3.64 g, 7 g and 10 g represent weight of salt added per 100 g soil).

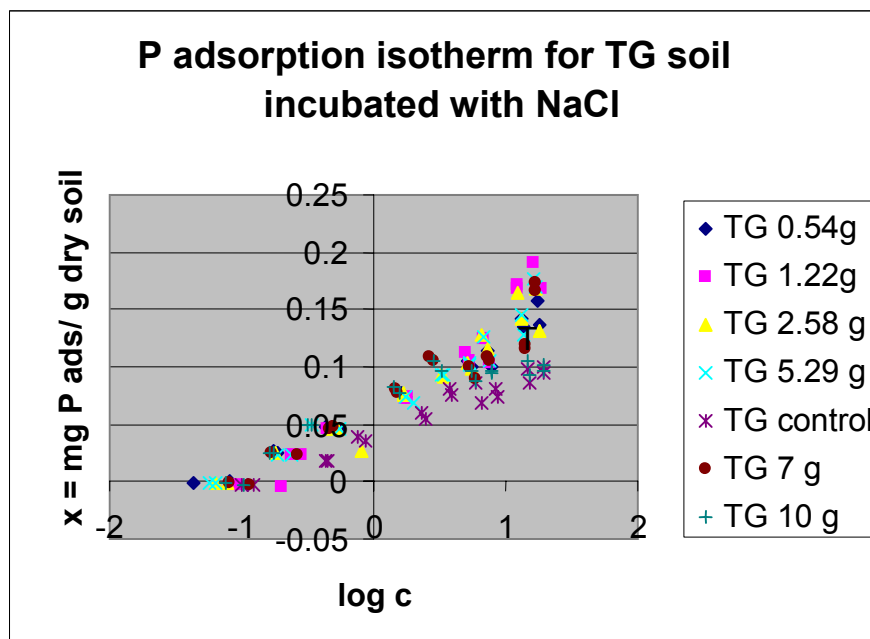


Figure 4.6. P adsorption isotherms for TG1 soil after incubation with NaCl salt (Control- no added salt, 0.54 g, 1.22 g, 2.58 g, 5.29 g, 7 g and 10 g represent weight of salt added per 100 g soil).

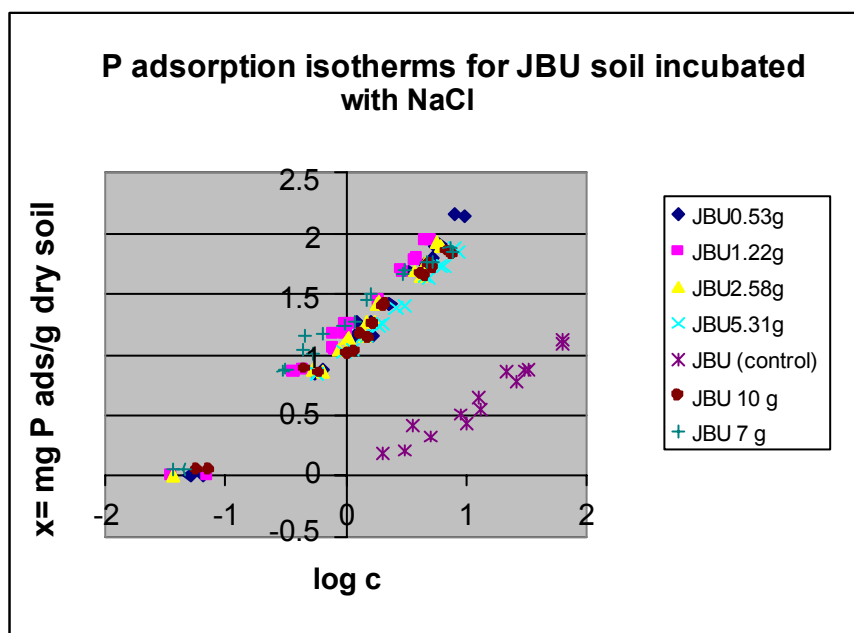


Figure 4.7. P adsorption isotherms for JBU1 soil after incubation with NaCl salt (Control- no added salt, 0.53 g, 1.22 g, 2.58 g, 5.31 g, 7 g and 10 g represent weight of salt added per 100 g soil).

Results of adsorption isotherms obtained by direct addition of salt to P sorption solutions are shown in **Figures 4.8, 4.9, and 4.10** for TG1, DP1 and JBU1 respectively. There were significant differences in P adsorption isotherms between control (no salt added) and salt solution addition treatments at all levels in JBU1 soil. The three levels of NaCl solution addition in JBU1 soil showed no difference in P adsorption. While the P adsorption isotherms for natural saline soil (DP1) showed no significant differences between the control (no additional salt) and added salt solution treatments at 0.04 mol/L NaCl, slight differences were found at concentrations of 0.08 and 0.12 mol/L NaCl. Phosphorus adsorption isotherms for TG1 soil showed slight differences at 0.04 and 0.12 mol/L with the control, but there was no significant difference between the control and adsorption at 0.08 M NaCl. **Appendix 4** includes full results for each treatment for 3 soils, plus P isotherm figures ($\log c$ vs. x) and their correlations.

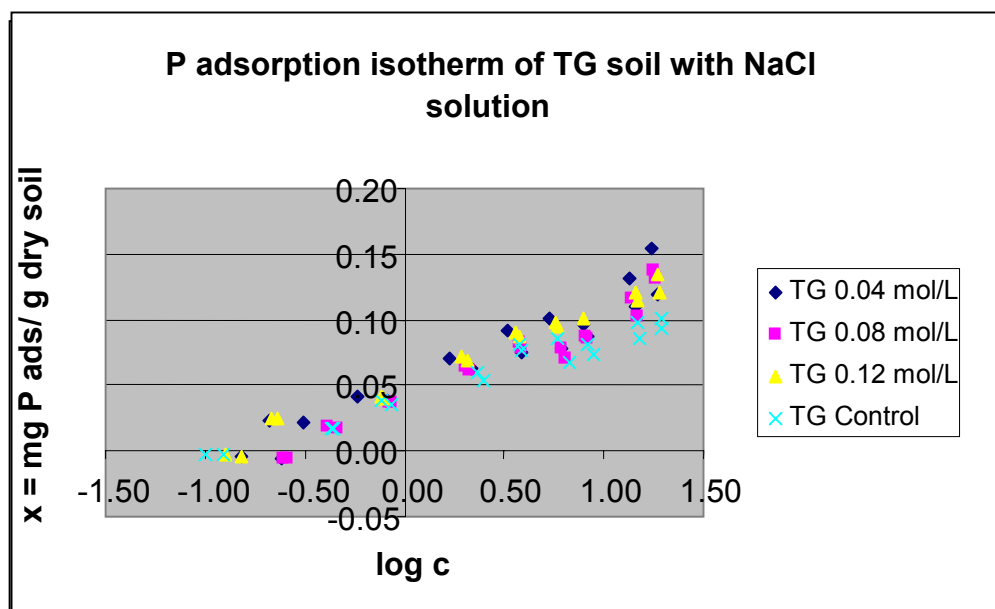


Figure 4.8. Adsorption isotherms of TG1 with NaCl addition to reaction solution.

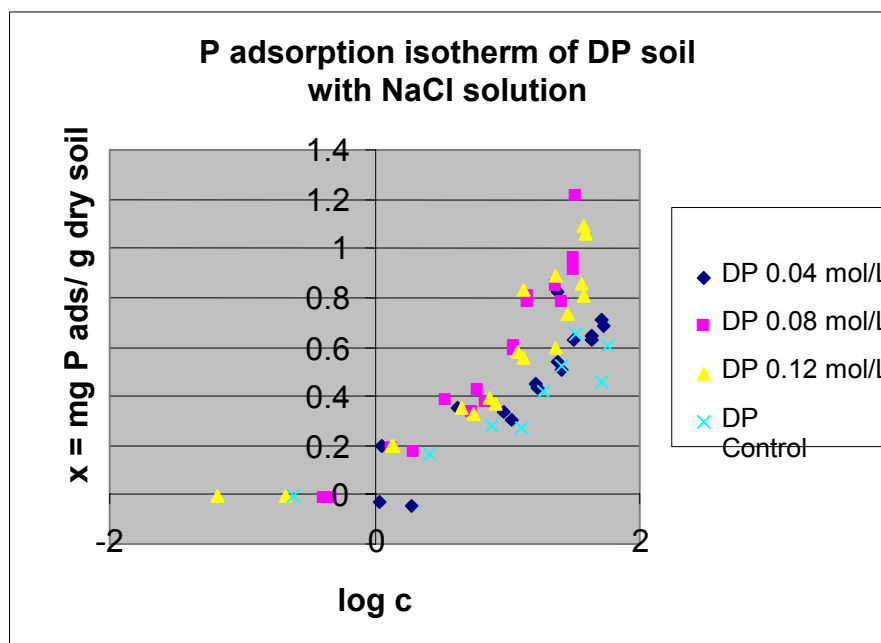


Figure 4.9. Adsorption isotherms of DP1 with NaCl addition to reaction solution.

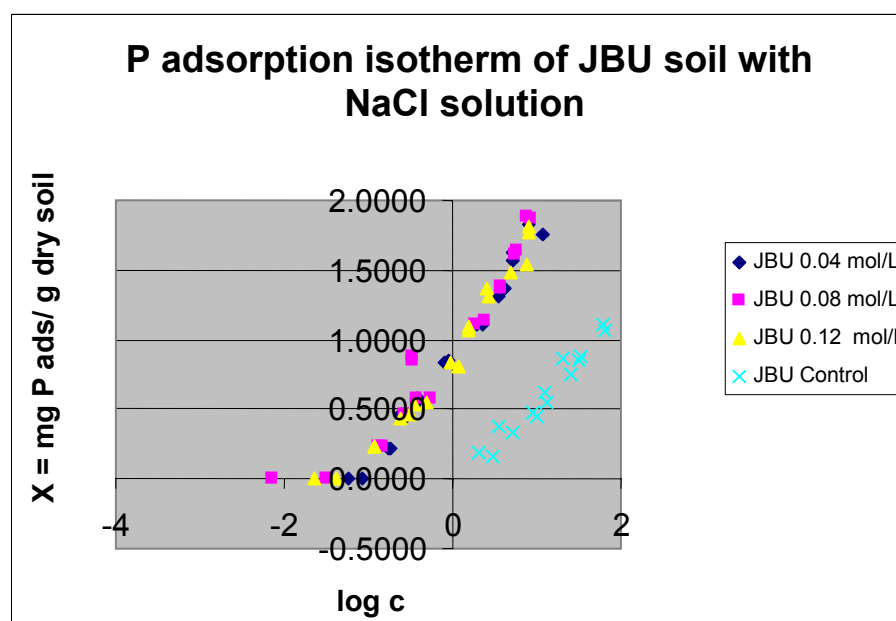


Figure 4.10. Adsorption isotherms of JBU1 with NaCl addition to reaction solution.

Comparisons between the P maximum adsorption values obtained using the Langmuir Equation for the first and second procedures are shown in **Tables 4.1, 4.2** and **4.3** for JBU1, DP1, and TG1 respectively. Phosphorus sorption maximum values

were calculated from the linear forms of Langmuir Equation (see **Section 2.11**) by plotting the regression line between c and c/x . The reciprocal of the slope gave the maximum P sorbed (mg) by the soil (g). Phosphorus maximum adsorption values varied significantly with the NaCl concentration. The P sorption capacity of DP1 soil, as indicated by the values of the Langmuir P maximum, ranged from 0.65-1.47 mg/g dry soil. Phosphorus maximum adsorption for JBU1 soil ranged from 1.36-2.42 mg/g dry soil. The TG1 soil had P maximum values between 0.11-0.20 mg/g dry soil. When comparing the P adsorption maximum in each treatment (both procedures) to the control (in the absence of added salt) within a soil, P adsorption increased significantly when salt was added ($p < 0.05$). Al Falih (2001) reported similar findings that increased salinity increased P adsorption in soil. Ryden et al. (1977) also found that the amount of P sorbed increased with the presence of salt.

However, on gradually increasing the concentration of NaCl salt over the studied range 0.004-0.12 mol/L for JBU1 and TG1 and 0.003-0.12 mol/L for DP1, no significant changes were observed between P adsorption in the presence of NaCl salt at various concentrations. In JBU1 soil, the adsorption maximum values remained relatively constant with increasing salt concentration. In TG1 and DP1 soils, the adsorption values showed greater variation. This observation is in accord with data presented previously (Helyar et al., 1976b) that no significant difference in the amount of P adsorbed by several minerals was found in the presence of Na, K or Mg chloride salts at various concentrations. Bolan et al. (1986) suggested that at point of zero salt effect, salt was found to have insignificant change on the P adsorption. At the point of zero salt effect, the electrolyte concentration does not affect the amount of P sorbed due to the lack of charge that is held on the soil or

mineral. Slow P adsorption may continue after the initial saturation of surface sites and NaCl had no effect when P reached the maximum.

Table 4.1. P maximum adsorption for JBU1 established from Langmuir Equation.

Soil	Treatment	NaCl salt added	Salt conc. in P adsorption system (mol/L)	P adsorption maximum (mg/ g soil)
JBU1	Control	0 g	0	1.36±0.13
	Salt incubated with soil	0.53 g to 100 g soil	0.004	2.42 ±0.12
	Salt incubated with soil	1.22 g to 100 g soil	0.008	2.22±0.11
	Salt incubated with soil	2.58 g to 100 g soil	0.018	2.19±0.15
	Salt incubated with soil	5.31 g to 100 g soil	0.036	2.08±0.11
	Salt added in reaction solution	1 mL of 2 mol/L of NaCl	0.040	1.95±0.10
	Salt incubated with soil	7g to 100 g soil	0.048	1.97±0.10
	Salt incubated with soil	10 g to 100 g soil	0.068	2.11±0.11
	Salt added in reaction solution	2 mL of 2 mol/L of NaCl	0.080	1.99±0.10
	Salt added in reaction solution	3 mL of 2 mol/L of NaCl	0.120	1.91±0.10

Table 4.2. P maximum adsorption for DP1 established from Langmuir Equation.

Soil	Treatment	NaCl salt added	Salt conc. in P Adsorption system (mol/L)	P adsorption maximum (mg/ g soil)
DP1	Control	0 g	0	0.65±0.10
	Salt incubated with soil	0.38 g to 100 g soil	0.003	0.75 ±0.10
	Salt incubated with soil	1.47 g to 100 g soil	0.010	0.92±0.10
	Salt incubated with soil	3.64 g to 100 g soil	0.025	1.06±0.11
	Salt added in reaction solution	1 mL of 2 mol/L of NaCl	0.040	0.81±0.10
	Salt incubated with soil	7g to 100 g soil	0.048	0.73±0.10
	Salt incubated with soil	10 g to 100 g soil	0.068	0.73±0.10
	Salt added in reaction solution	2 mL of 2 mol/L of NaCl	0.080	1.47±0.13
	Salt added in reaction solution	3 mL of 2 mol/L of NaCl	0.120	1.12±0.11

Table 4.3. P maximum adsorption for TG1 established from Langmuir Equation.

Soil	Treatment	NaCl salt added	Salt conc. in P adsorption system (mol/L)	P adsorption maximum (mg/ g soil)
TG 1	Control	0 g	0	0.11±0.01
	Salt incubated with soil	0.54 g to 100 g soil	0.004	0.15±0.02
	Salt incubated with soil	1.22 g to 100 g soil	0.008	0.20±0.02
	Salt incubated with soil	2.58 g to 100 g soil	0.018	0.16±0.02
	Salt incubated with soil	5.29 g to 100 g soil	0.036	0.18±0.02
	Salt added in reaction solution	1 mL of 2 mol/L of NaCl	0.040	0.14±0.02
	Salt incubated with soil	7g to 100 g soil	0.048	0.16±0.02
	Salt incubated with soil	10 g to 100 g soil	0.068	0.11±0.02
	Salt added in reaction solution	2 mL of 2 mol/L of NaCl	0.080	0.14±0.02
	Salt added in reaction solution	3 mL of 2 mol/L of NaCl	0.120	0.14±0.02

Another support for non-significant change in P adsorption in the current study is the original pH of the 3 studied soils. Their pHs ranged from 4-8 (see **Appendix 3, Table A7** for soil properties). Based on the studies of Barrow et al. (1980) and Barrow (1984), for an increase in the ionic strength, such as salt content of a soil, P adsorption would be relatively unaffected or increased rather than reduced in this range of pH.

The pH was measured in the studied soils during the reaction with different added concentrations of P. In JBU1, soil pH ranged from 4.60-5.09, DP1 soil pH was 7.07-7.59 and TG1 soil pH was 4.25-4.91. From the obtained data, pH values were relatively constant for each soil. Therefore, it is unlikely that pH would have a major influence on adsorption in this situation.

The third procedure included salt effects on soil P adsorption in extended shaking times between the soils and NaCl solutions, prior to the addition of P and CaCl_2 . Two soils were included in this study; DP1 and JBU1. The results of the study are presented in **Table 4.4**.

When considering the ionic strength at control (no additional salt), 0.04, and 0.12 mol/L NaCl, there was no significant difference in P maximum adsorption for DP1 with a 16-hour shaking period with increasing NaCl concentration. JBU1 showed a slight increase in P adsorption when NaCl concentration was increased at 16 hour period. At 72 hour shaking time, JBU1 showed an increased P adsorption when NaCl concentration was increased from 0.04 to 0.12 mol/L. DP1 P adsorption maximum was decreased when NaCl concentration was increased. Therefore, in all treatments except in DP1 soil at 72 hour shaking period, P adsorption tended to increase when NaCl concentration was increased. Similar observations were found in

the experiments where P was sorbed in a solution containing CaCl_2 (10^{-2} mol/L) at 1.5 to 2.5 times greater than those sorbed from water (Ryden et al., 1977). Therefore, increasing ionic strength decreased P concentration in equilibrium solution during experiments, i.e., increased sorption.

Table 4.4. Effects of NaCl concentrations on P adsorption by soils after 2 different shaking periods.

Soil	Shaking time prior to P addition (hours)	Maximum P adsorption (mg P/g dry soil)		
		Control (no added NaCl)	0.04 mol/L NaCl	0.12 mol/L NaCl
DP1	16	0.57±0.06	0.55±0.06	0.61±0.06
	72	NA	0.65±0.07	0.46±0.05
JBU1	16	1.20±0.05	1.33±0.07	1.48±0.07
	72	NA	1.20±0.06	1.34±0.07

Note: NA= Data are not available

Maximum P adsorption value comparisons for each soil at different shaking durations (16 to 72 hours) at a given constant NaCl concentration, showed that DP1 soil at 0.04 mol/L NaCl showed no significant difference in P adsorption when the shaking time was extended from 16 to 72 hours. However, the same soil with 0.12 mol/L NaCl showed a decrease in P adsorption maximum when the shaking time was increased.

The JBU1 soil with 0.04 mol/L NaCl showed a slight P adsorption decrement when the shaking time was increased from 16 to 72 hours. Likewise, at salt

concentration of 0.12 mol/L NaCl, a 10% P maximum adsorption reduction was obtained when the shaking period was prolonged to 72 hours. Overall, increasing the shaking time resulted in a decrease in P adsorption. It is presumed that shaking with salt of soils possibly can induce some clay flocculation, reducing surface area and possibly reducing adsorption. As discussed earlier, maximum P adsorption data in earlier experiments (see **Tables 4.1** and **4.2** for JBU1 and DP1 soils respectively) showed similar values for control for both soils, however, with the other NaCl treatments, the values were much higher than data presented in **Table 4.4**. No single explanation for these differences has been found.

This present study confirms that equilibrating soil samples with P solutions of various known concentrations and determining the amount of phosphate taken from solution by the soil sample at each equilibrium solution phosphate concentration can establish P isotherms. Different soil types with different physical and chemical properties showed different values of P adsorption. The high clay content and the oxyhydroxide component contributed to the high P adsorption in JBU1 soil, whereas TG1 soil, containing a much higher sand content, showed a low capacity to adsorb P. The results fit with the concept that much P adsorption by soils can be attributed to chemisorption (discussed in **Section 2.10.1**) involved in ligand exchange between P and hydroxyl ions at Fe and Al oxyhydroxides similar to the observations by Parfitt (1978).

Adding salt increased the P maximum adsorption in soils but further increases in NaCl concentration from 0.003 to 0.12 mol/L showed that there was no increment in P adsorption. No significant relationships were observed between salt concentration and P adsorption in the studied range. Similar trends were found in all 3 soils studied. This indicates that variations in NaCl concentrations ranging from

0.003-0.12 mol/L did not greatly influence P sorption by these soils. Differences in shaking time of soil with saline solutions resulted in a slight decrease in P adsorption with an increase in shaking period.

4.3 Sand Properties

As noted in **Section 3.6**, the sand was sieved ($< 500\ \mu\text{m}$) and acid washed before use. Properties of the sand (before use) in pot experiments are presented in **Table 4.5**.

Table 4.5. Sand properties for pot experiments.

Sand Property	Value
pH	4.18 \pm 0.01
EC (dS/m)	0.07 \pm 0.01
Water Holding Capacity (g/kg)	250 \pm 0.5
Available P (mg/kg)	< 0.001
P maximum adsorption (mg/ g sand)	Sand desorbed P

The data shown in **Table 4.5** reveals that sand had effectively no soluble salts present. The P adsorption isotherm for the sand showed that the sand gradually desorbed a very small amount of P rather than retained P to interfere with the plant growth.

4.4 Seed Germination

As reported in **Section 3.8**, a series of seed germination trials was completed. The rate of germination provided data on the numbers of seeds in each species to be sown in a pot. **Table 4.6** presents the germination rates of pasture species in sand in the absence and presence of salt at various concentrations.

In the absence of salt, legumes germinated faster than the grasses. Legumes generally took about a day to germinate, while grasses took longer periods (3-4 days) for germination. The rate of germination (no salt present) of all pasture species was 70-90% and all seedlings appeared healthy. In pot experiments, the numbers of seeds sown at the beginning of the experiments were higher than the actual numbers of plants harvested. This was to allow for non-germination of some seeds; seedlings were thinned after germination to pre-determined equal numbers in each pot.

Germination rates were compared between non-saline and saline trials to determine the effect of salt on germination. Balba (1995) suggested that the effect of salinity on germination can be presented as the proportion of plants emerging from a saline soil expressed as a percentage of those emerging from a non-saline soil. Tolerance to salinity at emergence is based on survival, whereas tolerance after emergence is based on decrease in growth or yield (Maas and Hoffman, 1977).

When salinity was added at different rates, the germination rates of plants under saline conditions showed that seeds took longer periods to germinate at higher salinity levels, e.g., with salinity above 4 dS/m, seeds took more than a week to germinate (**Table 4.6**). Salinity therefore, caused a considerable delay in germination.

Table 4.6. Germination rates of pasture plants at different salinity levels.

Species	Salinity level (dS/m)	Relative germination rate (%)	Time (day)
White clover	0	70	1
	2	30	>1
	4	20	>7
	8	0	
	12	0	
Red clover	0	90	1
	2	50	>1
	4	20	>7
	8	0	
	12	0	
Orchard grass	0	70	4
	2	50	>7
	4	20	>7
	8	0	
	12	0	
Birdsfoot trefoil	0	70	2
	2	60	>2
	4	50	>7
	8	20	>7
	12	0	
Ryegrass	0	90	3
	2	80	>3
	4	50	>7
	8	30	>7
	12	0	

The germination rates of all plants studied were reduced as salinity increased and no germination was found at salinity levels of 8 dS/m, except in birdsfoot trefoil and ryegrass. Where salinity was imposed at 12 dS/m, no germination was observed

for all species. Hayward and Bernstein (1958) and Mer et al. (2000) noted that some plants have greater sensitivity to salinity during the germination and early seedling growth than in later stages of growth development. If the salt concentration was high enough, no germination occurred (Hayward and Wadleigh, 1949). Similar results were observed in cowpeas, corn, African millet, beans, clover and vetch where germination rate was delayed and retarded by salinity. The higher the salinity level, the more was germination impaired (Ravikovitch and Porath, 1967). Hayward and Bernstein (1958) also noted that poor germination, or poor seedling emergence, are characteristics of plant growth under saline conditions. Studies on tree seeds of *Sesbania sesban* under saline conditions revealed that germination in soil-filled pots was reduced by salinity (Arshad and Hussain (1984) cited in Marcar et al., 1999). Increasing the concentration of NaCl in the range 0 to 600 mol/m³ delayed the germination and decreased the rate of germination and final germination percentage of 10 populations of *Prosopis farcta* (Dafni and Negbi (1978) cited in Marcar et al., 1999). Selassie and Wagenet (1981) reported reduced plant populations by soil salinity due mainly to the effects of salts upon germination.

In this study, increasing concentrations of salt reduced and delayed germination in all species. The reduced germination in the presence of salinity may be due to reduced water uptake (a result of high osmotic pressure), inability of the seeds to take up water for embryo expansion and/or toxicity to the embryo and physiological process alteration of seedling, e.g., enzyme activation, cell division and cell differentiation as has been observed by many workers (e.g., Hayward and Wadleigh, 1949; Croser et al., 2001).

Considering the germination rates of the species in this study, ryegrass showed the highest ability to tolerate salinity, with germination found even at a salinity of 8

dS/m with a 30% germination rate. White clover and red clover gave lower germination rates when salinity was increased, showing their sensitivity to salt. Germination was observed in orchard grass and birdsfoot trefoil at higher salinity when compared to red clover and white clover. The study of relative tolerance of forage crops and pasture plants has shown that red clover and white clover are considered as having poor salt tolerance, while birdsfoot trefoil and ryegrass were considered as having moderate salt tolerance and orchard grass is moderately salt sensitive (Bernstein, 1964a; Maas, 1986; Wolf, 1999).

In summary, salinity reduced and delayed seed germination. Salinity levels greater than 4 dS/m for clovers and orchard grass, and 8 dS/m for birdsfoot trefoil and ryegrass led to failure in seed germination. Grasses showed higher salt tolerance than legumes during germination.

4.5 Assessment of Optimal P Addition Rates for the 5 Pasture Species

As outlined in **Section 3.10.1**, experiments were set up to determine the optimum P requirement for the plant species being studied under the experimental conditions utilized. This information was required for planning of experiments where P and salinity levels were to be varied. Initially, studies examined the full range of P concentrations found in the literature (0-800 ppm).

The results from the first experiment are shown in **Figures 4.11, 4.12, 4.13, and 4.14** that illustrate yields of pasture plants responding to different levels of P. Legumes showed maximum growth at a P concentration of 50 ppm (red clover and birdsfoot trefoil) while the grasses produced good growth at 25 ppm P. There was no significant difference in the yield of orchard grass at P levels ranging from 25 to 200

ppm and from 25 to 100 ppm in ryegrass. Significant differences were found for all species only when comparing all P treatments with the control (no P applied- 0 ppm P) ($p < 0.05$). Among the grasses, ryegrass gave the best response to P as can be seen from the yields produced. The results showed that legumes appeared to require higher levels of P to gain the optimal growth compared to the grasses.

In the experimental treatments where no P was added, plants showed symptoms of stunted growth compared to those plants at higher levels of P (e.g., see **Figure 4.15** for red clover). Similar observations where P was deficient for plants have been noted by other research workers (Thorne and Peterson, 1954; Loneragan and Asher, 1967; Troeh and Thompson, 1993; Brady and Weil, 1996; Havlin et al., 1999; Dilli, 1999). They reported that at low external P levels, rates of P adsorption may be insufficient to maintain tissue P at the concentrations needed for healthy growth, therefore, plants at low initial P concentration showed symptoms of P deficiency and poor growth.

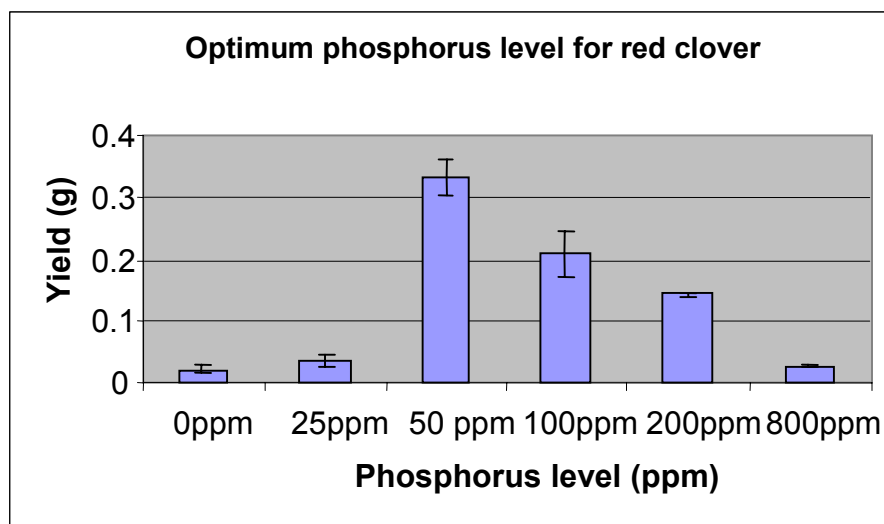


Figure 4.11. Red clover yield (g) and P level after 12 weeks.

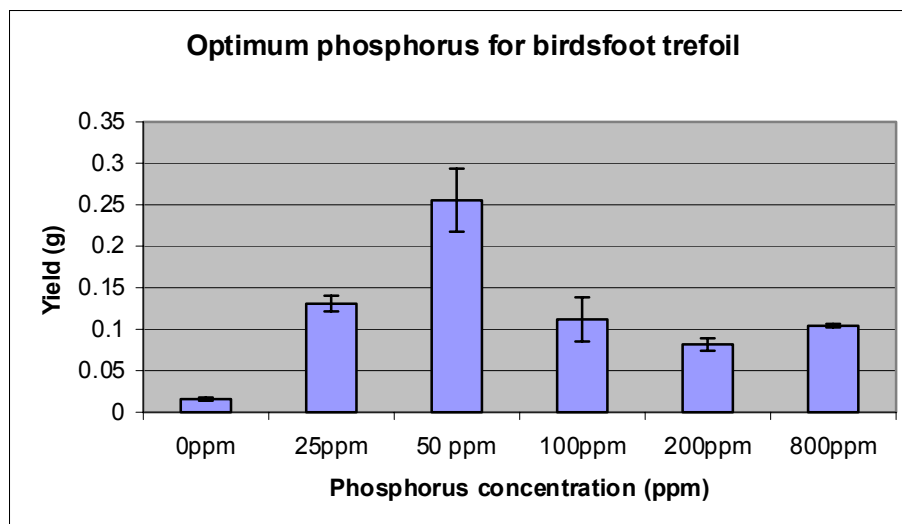


Figure 4.12. Birdsfoot trefoil yield (g) and P level after 12 weeks.

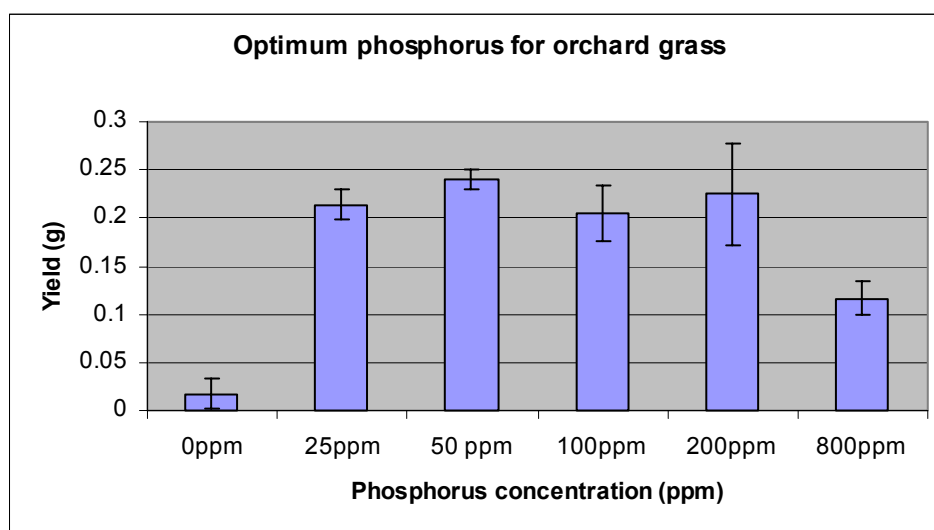


Figure 4.13. Orchard grass yield (g) and P level (ppm) after 12 weeks.

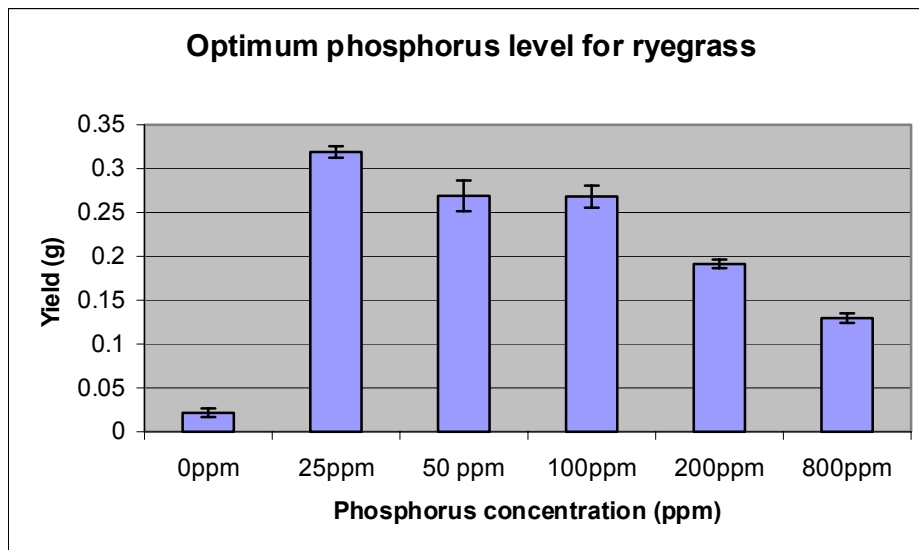


Figure 4.14. Ryegrass yield (g) and P level (ppm) after 12 weeks.



Figure 4.15. Red clover morphology at 6 levels of P after 12 weeks (Treatments are, from left to right, 0, 25, 50, 100, 200 and 800 ppm P).

At P concentrations higher than the optimum levels, i.e., at 200 ppm and 800 ppm, plant yields tended to decrease. A possible explanation is that there is a certain level of P where plants respond to give the best yields, and beyond that level, plants

cannot utilize additional nutrient. Additions of excessive level of P and other nutrients have been shown to reduce plant yields. Once the maximum rate growth for a given species under a given environmental conditions has been reached, further increases in the rate of mineral absorption may result in accumulation of elements in concentrations higher than necessary for maximum growth, and such accumulation may cause a reduction in growth rate (toxicity) (Loneragan and Asher, 1967). Ravikovitch and Yoles (1971), for example, reported that P at 19.2 ppm was the optimum level for millet in non-saline and saline treatments, but additional application of P in excess of this level had no beneficial effect on plant development and in some cases raising the P level above the optimum range somewhat reduced the yield. Growth depressions associated with high concentrations of P have also been reported in barley, clover, lupin, oats and soybeans (Loneragan and Asher, 1967). In the present study, tip burn of leaves in ryegrass and red clover was observed in some treatments at 800 ppm P. Bernstein et al. (1974) noted that visible injury symptoms such as the presence of marginal tip burn in leaves were strongly apparent associated with excess P or deficient P levels.

The experiment with high P levels was conducted to cover the range of concentrations found in the literature review. These high ranges were, however, excessively wide to evaluate the effect P on the development of plants. When a high P concentration range was used, the first P value (above the control) often gave the optimal response. This led to the question - was the first P level the optimal, or was it above the optimal, i.e., did the response follow curve A or B in **Figure 4.16**?

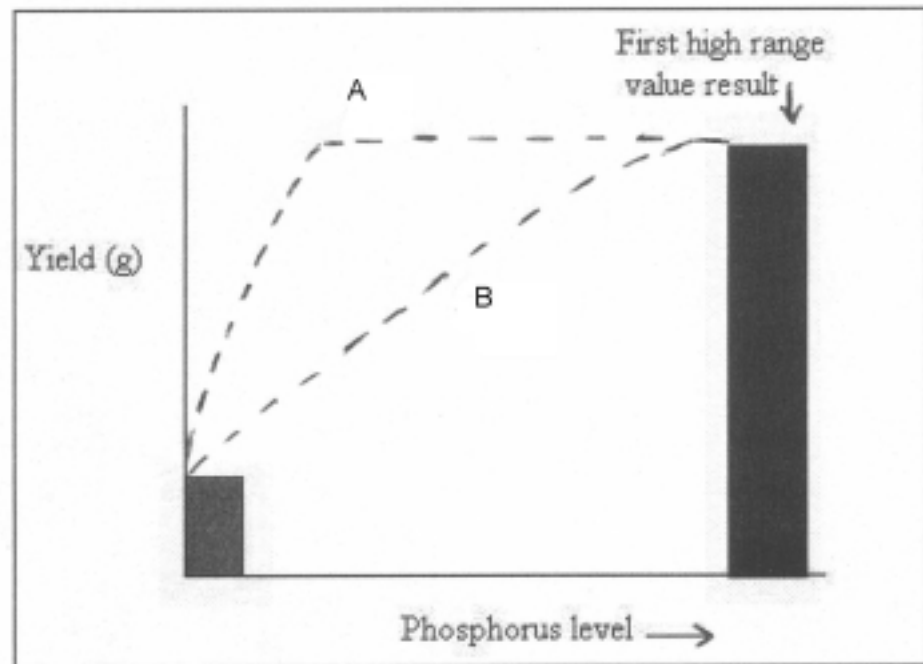


Figure 4.16. Possible response curve of pasture plants to varying P additions.

As mentioned in **Section 3.10.1.1**, in order to ascertain this, supplementary experiments were set up to examine, in more detail, the P response of the plants over an extended lower range of P concentrations; 0, 0.01, 0.1, 0.5, 1.0, 5.0 and 25 ppm P (added as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$).

The first set of low P range experiment was set up in the greenhouse under identical conditions to the previous experiment except for the low concentrations of P. Water was added from the top of the pots. The results are shown in **Figures 4.17, 4.18, 4.19** and **4.20** for red clover, birdsfoot trefoil, orchard grass and ryegrass respectively. The best yield was obtained at 25 ppm P for all species. There was no significant difference in yield between control (no P) and other low P levels (0.01-5 ppm), i.e., yield did not increase, when P was raised up to 5 ppm. However, there

was a marked change in yield when P reached 25 ppm. Ryegrass presented the best growth at the highest P level, whereas birdsfoot trefoil gave the lowest dry material yield.

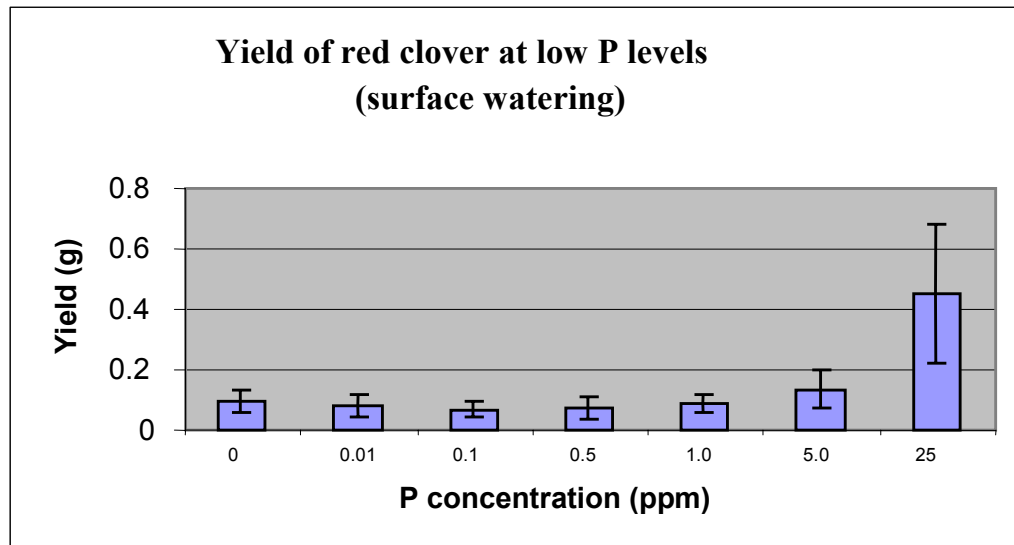


Figure 4.17. Red clover yield with low range of P levels after 12 weeks.

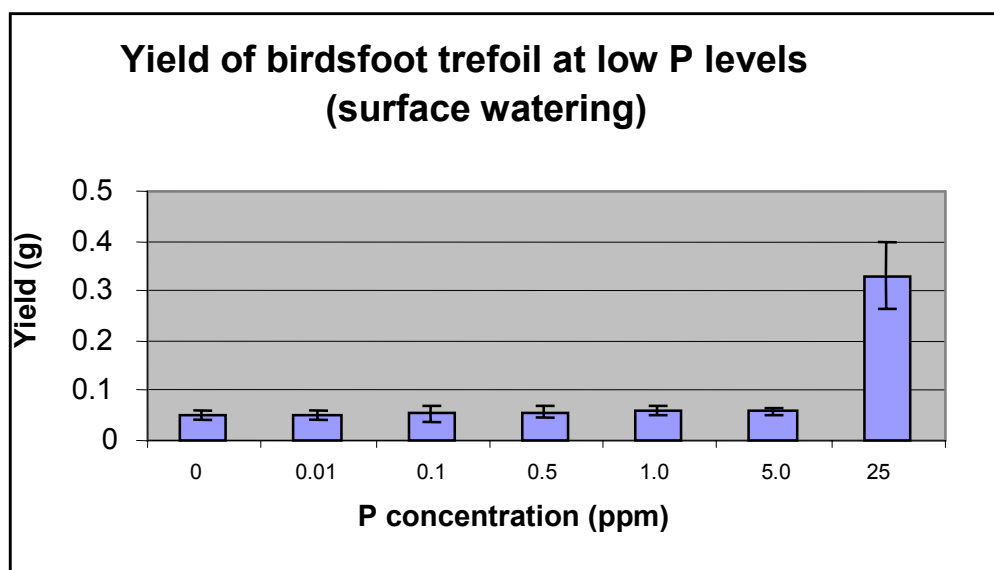


Figure 4.18. Birdsfoot trefoil yield with low range of P levels after 12 weeks.

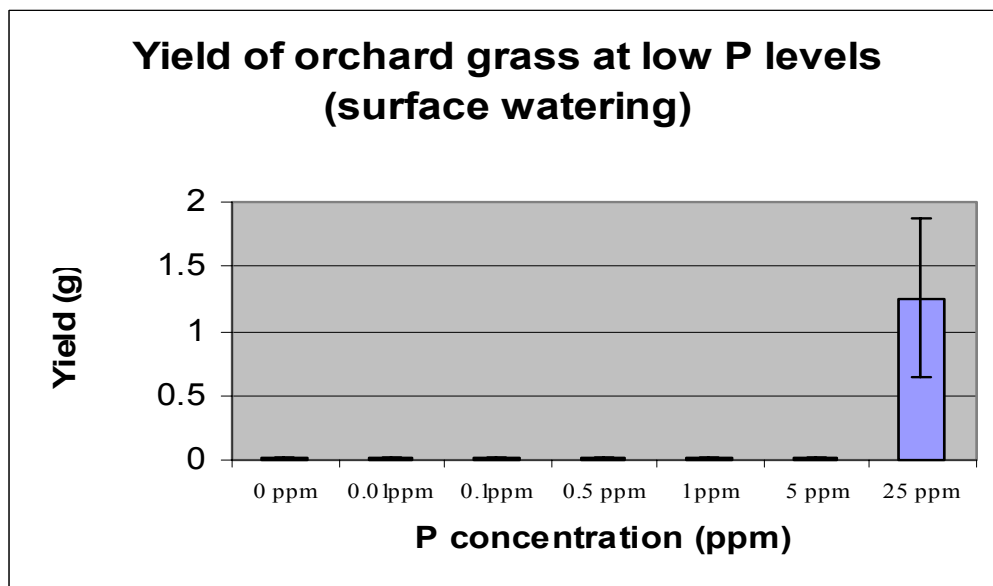


Figure 4.19. Orchard grass yield with low range of P levels after 12 weeks.

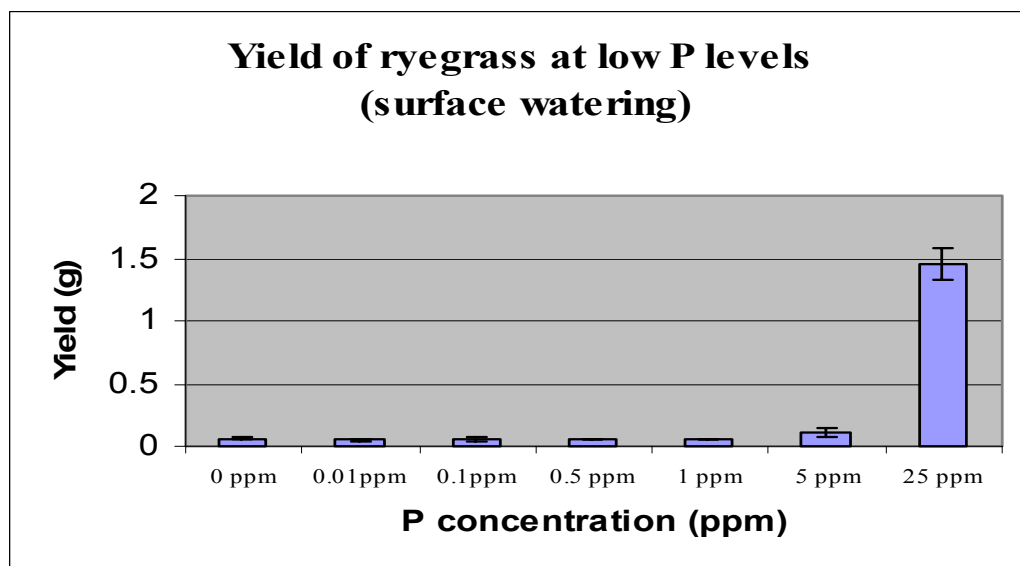


Figure 4.20. Ryegrass yield with low range of P levels after 12 weeks.

When considering the optimal P, the results indicated that there was low response of plants at low P levels (0-5 ppm). This was somewhat unexpected as the literature states that some plants have quite low optimal solution P concentrations

(e.g., Havlin et al. (1999) suggested P required in most plants is between 0.03-0.3 ppm depending on crop species and level of production, and Brady and Weil (1996) noted that a concentration of 0.2 mg P/L in the soil solution is adequate for optimum growth of most crops).

Four possible hypotheses were developed to explain why plants gave the best yield at P concentrations of 25 ppm or higher:

- 1) Plants could not access the added P where P concentrations were at low levels;
- 2) Added P was washed down to the bottom of the pots when watered from the top especially at low levels of P, thus making it unavailable to young plants;
- 3) Interference complexation between added P and other elements, rendering P unavailable; and,
- 4) P adsorption on sand.

The preliminary studies on P adsorption (or lack of it) by sand tended to eliminate option 4. Calculations of various solubility products with P and other elements indicated no products were likely to render P unavailable, removing option 3, so only options 1 and 2 were feasible.

To investigate options 1 and 2 further, a second set of experiment was designed as described in **Section 3.10.1.1**, where instead of watering from the top, water was added via syringe which was connected to the small tube and inserted to the middle of each pot. Furthermore, the new experimental design also permitted clarification of the watering issue and any interference with the experiment response

to P addition. Sand used was analysed after the experiment for P, pH, and EC to assist possible explanations of the observations.

The growth response results obtained in this second experiment with lower concentrations of P applied at 0, 0.01, 0.1, 0.5, 1.0, 5.0 and 25 ppm, are shown in **Figures 4.21, 4.22, 4.23 and 4.24** for legumes and grasses.

The best growth response was found at 25 ppm for all species and was significantly different from the control ($p < 0.05$) and the other P concentrations. Comparing yields in the control (in the absence of P) and other low P concentrations (0.01, 0.1, 0.5, 1.0 and 5.0 ppm) showed they were very low compared to those obtained at 25 ppm except in ryegrass where yield at 5 ppm P was relatively high.

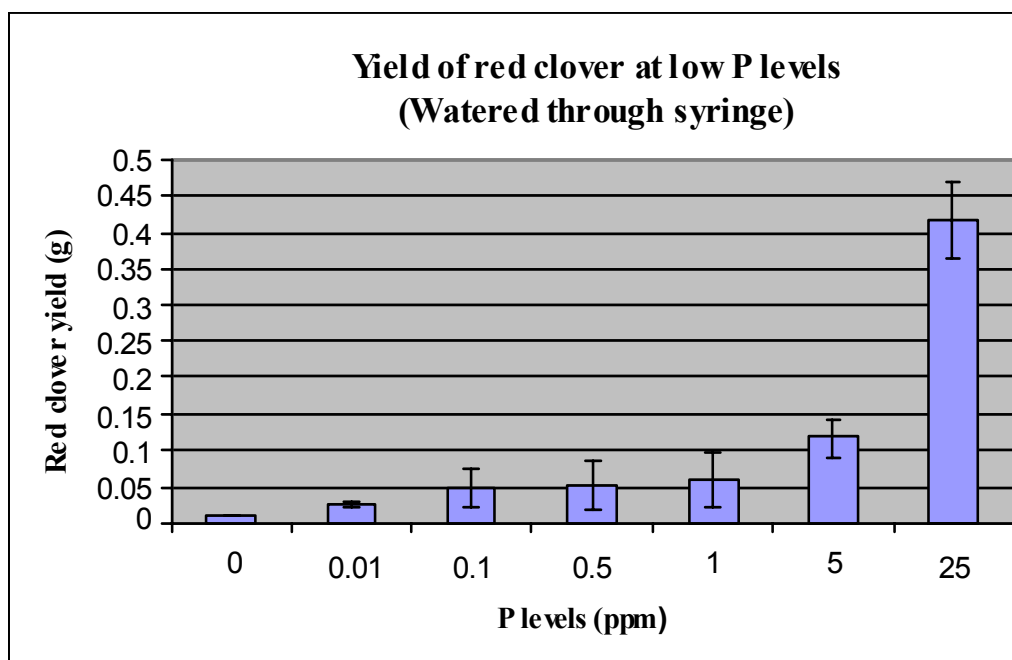


Figure 4.21. Yield comparison at 7 levels of P for red clover after 12 weeks.

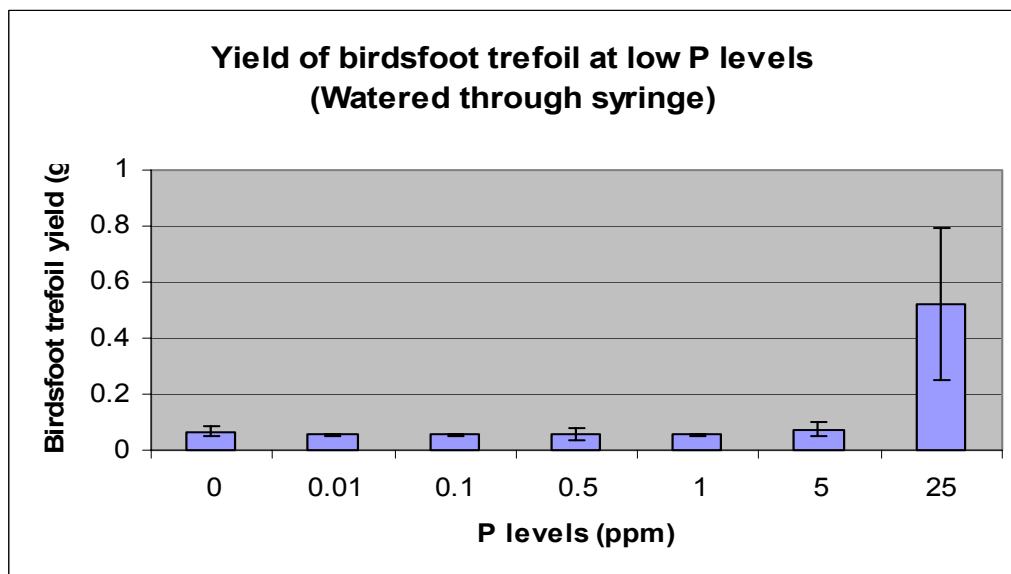


Figure 4.22. Yield comparison at 7 levels of P for birdsfoot trefoil after 12 weeks.

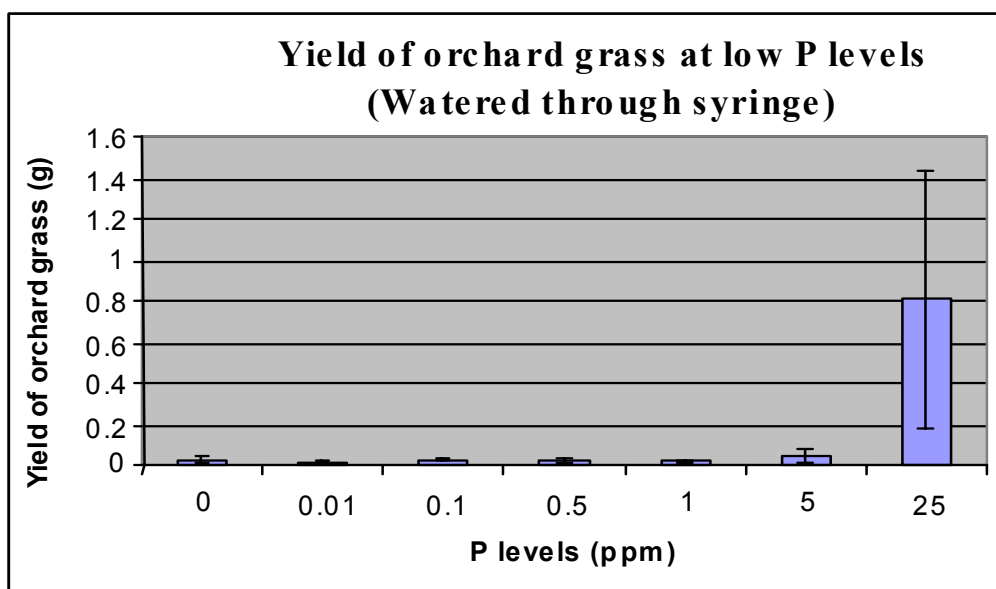


Figure 4.23. Yield comparison at 7 levels of P for orchard grass after 12 weeks.

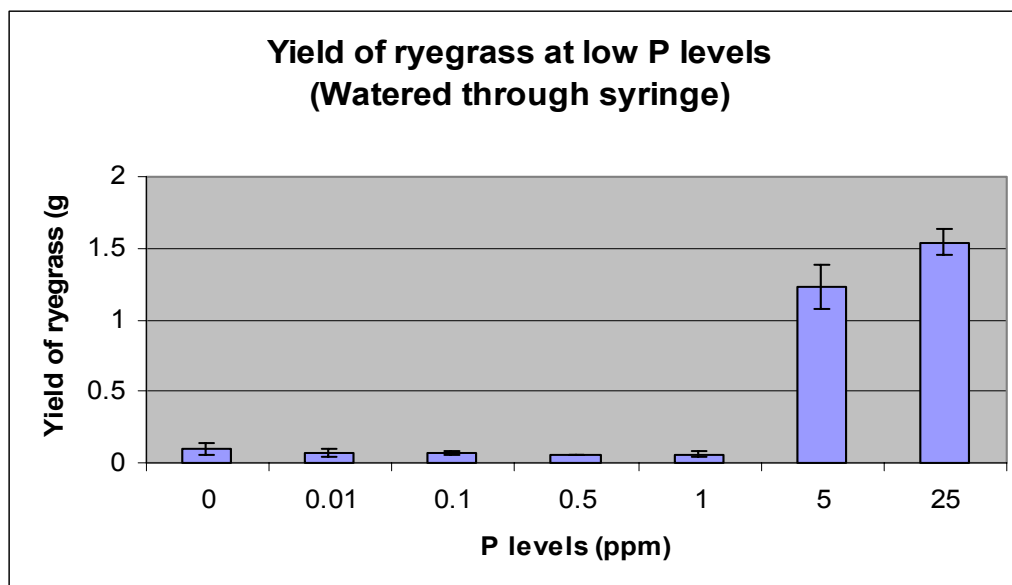


Figure 4.24. Yield comparison at 7 levels of P for ryegrass after 12 weeks.

Tables 4.7, 4.8, 4.9 and 4.10 show selected elemental compositions of plants grown in different levels of P solution present in the cultures. **Table 4.11** presents the sufficiency values of selected elements in plant tissues. The comparisons between the experimental values and “recommended” values provide guidance for interpreting plant growth responses (see **Section 2.6.1**).

In red clover, due to insufficient materials, only plants from 0 and 25 ppm added P treatments were analysed for tissue contents (**Table 4.7**). The P content in the tissue increased as the added P solution increased from 0 to 25 ppm. Ca, S, Zn contents in the tissues showed the same patterns as the P content. Mg and Mn in plant tissues showed no significant changes when the added P concentration was increased. Trace elements such as Al, Fe, Co, Ni, Mo, Cu and Cd in plant tissues tended to be lower at high P additions. Comparing to **Table 4.11** (plant tissue mineral contents in sufficiency ranges), the P content in red clover tissues was in sufficiency range for optimal growth in the 25 ppm added P treatment. High Ca, Fe,

Zn and Mo contents were observed when compared to the sufficiency ranges. Mg and K were found to be at sufficiency ranges for both P treatments while the S content was deficient at 0 rate of P but sufficient at the high P addition. Mn was at deficiency levels in both treatments.

Table 4.8 shows mineral contents for birdsfoot trefoil. The analysis showed that there was no significant change in P tissue content as added P was increased; this was also true for Na content. No patterns were found for the other studied elements. Comparing to **Table 4.11**, the P, Mg, K and S contents were found to be insufficient for plant growth in any added P treatment, whereas Ca, Na and Cu contents were in the sufficiency ranges. Zn was in excess at high added P (25 ppm P). Mn and Fe contents were high in all tissue samples.

Table 4.9 shows the mineral contents in orchard grass. A similar trend to birdsfoot trefoil was observed. P tissue content remained relatively constant as added P increased. There was no pattern for other mineral contents when P addition changed. When comparing data between **Table 4.11** and **Table 4.9**, the Na, Mg, K, S, Mn and Cu tissue contents were at the sufficiency requirements while P was deficient for all treatments. However, Ca, Fe and Mo contents in plant tissues were in excess in all P treatments.

Ryegrass tissue contents are shown in **Table 4.10**. The P content in the tissues tended to increase (but there was no significant increase) as added P increased. The Mg content also tended to increase slightly, but was no clear pattern for other elements. Comparing to **Table 4.11**, the P contents in plant tissues in this study were inadequate for optimal growth, while K, Mn and Zn contents were in the satisfactory ranges. The Ca and Fe contents were high, while the Mg content was

deficient at low concentrations of added P but found to be adequate at higher added P.

In summary, analysis of P content in plant tissues showed that plants in the low added P treatments were taking up little P. For all P treatments ranging from 0-25 ppm, the P content in plant tissue did not show any statistically significant differences except in red clover. However, comparing tissue contents for the plants with the P at 25 ppm and 0 ppm (control), the P content in plant tissues for 25 ppm samples was often nearly double the control for all studied species. This higher P concentration in plant tissues was closely related to yield, especially with red clover and ryegrass. As discussed earlier, the best growth response was found at 25 ppm for all species. This is similar to results of Ravikovitch and Yoles (1971) who reported that the P contents of plant tissue were function of the different rates of P application. Eleizalde et al. (1982) and Eleizalde et al. (1983) found that the P content of plant material was increased by P addition to soil.

Generally, the average amount of P found in plants is between 0.1 and 0.5%. However, from this experiment, it can be seen that only red clover had tissue P in the sufficiency range. The other species showed insufficient P tissue values. The Ca contents were often above plant requirements. Yaron et al. (1973) noted that Na sufficiency content values in plant tissues are between 0.01 and 0.04 % and the concentration of 0.5% will cause toxic symptoms in sensitive plants. The Na contents in plant tissues in this current study were not high enough to cause toxicity.

Table 4.7. Mineral compositions in red clover at different levels of P addition.

Treatment	Plant elements in red clover														
	P (%)	Na (%)	Ca (%)	Mg (%)	K (%)	S (%)	Al mg/ kg	Fe mg/ kg	Mn mg/ kg	Cd mg/ kg	Cu mg/ kg	Mo mg/ kg	Co mg/ kg	Ni mg/ kg	Zn mg/ kg
P =0 ppm	0.07	0.03	1.84	0.36	2.4	0.15	181	310	21	<3	<9	<8	<8	<10	25
P =0.01 ppm	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P =0.1 ppm	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P =0.5 ppm	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P =1.0 ppm	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P =5.0 ppm	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
P =25 ppm	0.20	0.02	4.30	0.35	1.76	0.21	95	163	20	<0.5	6.8	2.1	<1	<2	30

Note: NA= not available due to plant tissue was insufficient for analysis

Table 4.8. Mineral compositions in birdsfoot trefoil at different levels of P addition.

Treatment	Plant elements in birdsfoot trefoil														
	P (%)	Na (%)	Ca (%)	Mg (%)	K (%)	S (%)	Al mg/ kg	Fe mg/ kg	Mn mg/ kg	Cd mg/ kg	Cu mg/ kg	Mo mg/ kg	Co mg/ kg	Ni mg/ kg	Zn mg/ kg
P =0 ppm	0.02	0.01	11.4	0.20	0.69	0.11	170	390	44	<0.6	6.2	<1	<1	4.9	22
P =0.01 ppm	0.02	0.03	0.32	0.12	0.83	0.11	460	1480*	63	<2	16	<4	<4	14	22
P =0.1 ppm	0.02	0.01	18.4*	0.2	0.30	0.03	240	490	56	<1	6.1	3.0	<3	5.7	12
P =0.5 ppm	0.01	<0.004	4.6	0.12	0.49	0.06	89	199	21	<3	<7	<6	<6	<9	12
P =1.0 ppm	0.02	0.03	0.70	0.11	0.56	0.08	300	520	41	<2	6.1	<5	<5	11	13
P =5.0 ppm	0.02	0.004	12.0*	0.19	0.54	0.06	125	320	35	<1	<3	<2	<2	5.5	15
P =25 ppm	0.04	0.03	0.82	0.23	1.72	0.09	430	860	43	<0.5	13	1.4	<1	4.7	24

Note: NA= not available due to plant tissue was insufficient for analysis

* = Values considered in error

Table 4.9. Mineral compositions in orchard grass at different levels of P addition.

Treatment	Plant elements in orchard grass														
	P (%)	Na (%)	Ca (%)	Mg (%)	K (%)	S (%)	Al mg/ kg	Fe mg/ kg	Mn mg/ kg	Cd mg/ kg	Cu mg/ kg	Mo mg/ kg	Co mg/ kg	Ni mg/ kg	Zn mg/ kg
P =0 ppm	0.04	0.07	0.61	0.19	3.0	0.43	490	1780	88	<5	11	<10	<10	<20	46
P =0.01 ppm	0.03	0.04	4.30*	0.18	1.9	0.28	<200	570	100	<10	<30	<30	<30	<40	32
P =0.1 ppm	0.04	0.03	5.9*	0.22	2.6	0.39	97	460	141	<2	12	<5	<5	<7	48
P =0.5 ppm	0.05	0.02	5.9*	0.21	2.7	0.43	76	360	132	<2	10	<5	<5	<8	46
P =1.0 ppm	0.05	0.03	0.53	0.16	2.5	0.34	280	1590*	173	<5	<10	<10	<10	<20	38
P =5.0 ppm	0.05	0.04	0.57	0.23	3.2	0.43	220	870	156	<2	9.3	6.5	<5	<7	46
P =25 ppm	0.05	0.03	2.8*	0.25	3.9	0.26	46	220	51	<0.4	11	3.7	<0.9	5.3	39

Note : NA= not available due to plant tissue was insufficient for analysis

* = Values considered in error

Table 4.10. Mineral compositions in ryegrass at different levels of P addition.

Treatment	Plant elements in ryegrass														
	P (%)	Na (%)	Ca (%)	Mg (%)	K (%)	S (%)	Al mg/ kg	Fe mg/ kg	Mn mg/ kg	Cd mg/ kg	Cu mg/ kg	Mo mg/ kg	Co mg/ kg	Ni mg/ kg	Zn mg/ kg
P =0 ppm	0.03	0.02	5.00	0.18	1.74	0.40	90	250	78	<0.8	8.4	<2	<2	5.6	39
P =0.01 ppm	0.03	0.04	2.60	0.18	1.96	0.46	46	188	90	<2	9.4	<4	<3	<5	37
P =0.1 ppm	0.04	0.03	2.30	0.22	2.4	0.61	44	220	122	<0.9	12	<2	<2	5.0	49
P =0.5 ppm	0.04	0.04	3.10	0.22	2.0	0.50	50	210	84	<2	8.3	<5	<5	<7	63
P =1.0 ppm	0.04	0.04	3.10	0.22	1.87	0.52	75	250	77	<1	14	3.5	<3	4.2	45
P =5.0 ppm	0.05	0.05	3.50	0.24	3.1	0.55	57	220	114	<0.4	13	3.9	<0.9	8.3	51
P =25 ppm	0.06	0.04	0.56	0.25	2.4	0.26	41	350	3	<0.4	8.7	2.6	<0.9	17	30

Table 4.11. Summaried reference selected plant tissue mineral contents in sufficiency ranges for legumes, orchard grass and ryegrass (Reuter and Robinson, 1986; Plank, 1999).

Plants	P (%)	Ca (%)	Mg (%)	K (%)	S (%)	Fe (mg/kg)	Mn (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Mo (mg/kg)
Legume	0.20-0.30	0.40-0.50	0.25-0.30	1.75-2	0.20-0.25	50-85	25-30	15-19	>5	0.15-0.2
Orchard grass	0.25-0.35	0.35-0.50	0.15-0.30	2.5-3.5	0.20-0.30	50-250	50-200	20-50	3-10	>0.1
Ryegrass	0.20-0.40	0.25-0.30	0.20-0.35	1.5-3.0	0.27-0.32	50-80	50-300	15-30	5-12	0.3-0.4

In this experiment, plants were observed daily and visible growth features noted. Plant growth prior to maturity appeared stunted in the non-P treatments. Yellowing was also observed in some plants in low P treatments. Similar observations of P deficiency symptoms in plants have also been found in many studies (e.g., Thorne and Peterson, 1954; Troeh and Thompson, 1993; Brady and Weil, 1996; Havlin et al., 1999; Dilli, 1999). Therefore, the injuries observed in some plants in this study possibly resulted from insufficient P and high Ca content in the tissues. Deficient P in plant tissues was possibly a result of low pH in the pots (see **Table 4.12** for sand separates after completion of pot experiment). Low pH would contribute to low available P to plants. The results suggest that a higher P treatment should be investigated to determine if the sufficiency range could be obtained (see **Sections 3.10.3** and **4.7** for P at 35 ppm).

Ryegrass produced the highest yield of the species studied; this is in line with its characteristic high yield potential (Hannaway et al., 1999). Grasses responded to higher levels of P better than legumes. This observation was supported by Maas and Hoffman (1977) who also found that grasses preferred higher levels of P than legumes and produced more biomass. Wright et al. (1984) also found that plants which develop an effective mycorrhizal association (legumes) have a lower external P requirement than plants without mycorrhiza. However, there are many factors associated with P level that can affect the maximum growth, such as, the environment and the method of determining solution P. The results obtained in this experiment were used to set the levels of P in later experiments where various levels of salinity were applied in sand pot cultures (as mentioned in **Sections 3.10.3** and

4.7). Phosphorus at 25 ppm was used as the optimal P level for ryegrass in later experiments (**Section 3.10.2** and discussed in **Section 4.6**).

Rooting habits were observed after harvesting. The observations showed that ryegrass and orchard grass produced, in all treatments, greater root distribution to the deeper parts of the pots, whereas red clover roots remained close to the surface. Birdsfoot trefoil's root distribution was also generally close to the surface but more widely distributed than red clover roots. Greater root distributions in ryegrass and orchard grass may be related to higher yields obtained, compared to the other 2 species. Root activity associated with yield was found by Martin et al. (2002); they found that ryegrass showed high efficiency in extending root surface to utilise more P and displacing bound P from P-goethite complexes can increase P desorption which contributed to its large yields.

In this present study, the observations of limited root development clearly show that for some plants, full use was not made of the added P as the roots did not reach areas where some P would have been located.

After the experiment, the sand in the pots from ryegrass experiments was separated into 2 parts: top half and bottom half. **Table 4.12** shows results of the sand analyses. The pH and EC of sand both from the top and lower parts were relatively constant. Available P in the bottom parts was slightly higher than the top parts of the pots for the 25 ppm treatments, suggesting either that P solution moved down towards the bottom of the pot during the experiment or that more P was used by plants from the upper parts of the pots. The differences are not large enough to explain why the plant roots in some pots did not move further, unless for very low P values, they were affected by the relatively low pH values.

A small trial was also set up to assess the difference between the 2 watering methods; through the surface and through the syringe, on sand properties. The results (not presented) showed that pH, EC, and available P were relatively constant throughout the pots. Therefore, it can be concluded that the method of watering was not a major factor influencing the experimental results.

The pattern of results for the low range P experiments is unusual. No specific explanation can be provided for the response curve, other than the possible influence of low pH on root distribution for some plants.

Table 4.12. Analytical data for sand separates after completion of ryegrass plant growth experiment (low range P).

Treatment	pH	EC (dS/m)	Available P (mgP/kg)
P= 0 ppm Top half	4.87	0.1	0.0018
P=0 ppm Bottom half	5.17	0.09	0.0018
P = 5 ppm Top half	5.53	0.08	0.0016
P = 5 ppm Bottom half	5.48	0.09	0.0012
P= 25 ppm Top half	5.78	0.08	0.0023
P=25 ppm Bottom half	5.98	0.07	0.0028

Information on acidity tolerance in studied species shows that orchard grass is tolerant to acidic soils and prefers pH between 5.5 and 8.2. Ryegrass tolerates both acidic and alkaline conditions with pH preference between 5.1 and 8.4. Red clover grows well on a wide variety of soil types and prefers pH between 6.2 and 6.8.

Birdsfoot trefoil gives the maximum growth on soils with pH between 6.0 and 6.2. Therefore, it is possible that in some treatments especially with low added P concentrations where pHs were lower than plant preference (e.g., pH <5), plants encountered unfavourable conditions and produced unsatisfactory growth.

In summary, P response for each species was variable depending on plant demand, period of time and stages of growth. The highest yield, in all studied plants in this experiment, was obtained at 25 ppm P level. At the optimum P value, ryegrass exhibited the best growth producing the highest yields among studied plants, while red clover had the lowest yields. Visible injury was observed in plants in unfavourable conditions. In control experiments with no P addition, plants showed deficiency symptoms such as stunted growth, thin stems, delayed maturity and poor root development. Similar observations have been reported regularly elsewhere (Thorne and Peterson, 1954; Troeh and Thompson, 1993; Brady and Weil, 1996; Havlin et al., 1999).

4.6 The Effect of Salinity on Growth of Ryegrass at Optimal P Conditions

Ryegrass was selected for this study as it produced the highest yields in previous experiments and also its salt tolerance ability. The objective of this study was to observe variations in ryegrass yield under various levels of salinity where P was added at the optimum level as mentioned in **Section 3.10.2**. In this study with the constant P, 5 levels of salinity were used: control (no salt added), 2, 4, 8 and 12 dS/m. Plants were harvested twice (after 7 weeks and 12 weeks). The yields obtained are presented in **Figure 4.25**.

After 7 weeks growth, yields showed significant decrease as the degree of salinity was increased. At the highest salinity (12 dS/m), plants were unable to produce any biomass due to seed germination failure. The yield response was 54, 22, 12 and 0 % of the control for 2, 4, 8 and 12 dS/m treatments respectively.

Yields in second harvest (after 12 weeks), however, showed a slightly different trend. There was a significant difference in yield between control and at 8 dS/m. Yield at 2 dS/m was different slightly to the control. The yield response was 87 and 72 % of the control for salinity at 2 and 8 dS/m. There was a general trend of yield decreases with increasing salinity, but yield at 4 dS/m was similar to the control. The yield of plants in the second harvest was less affected by salinity compared to the first one.

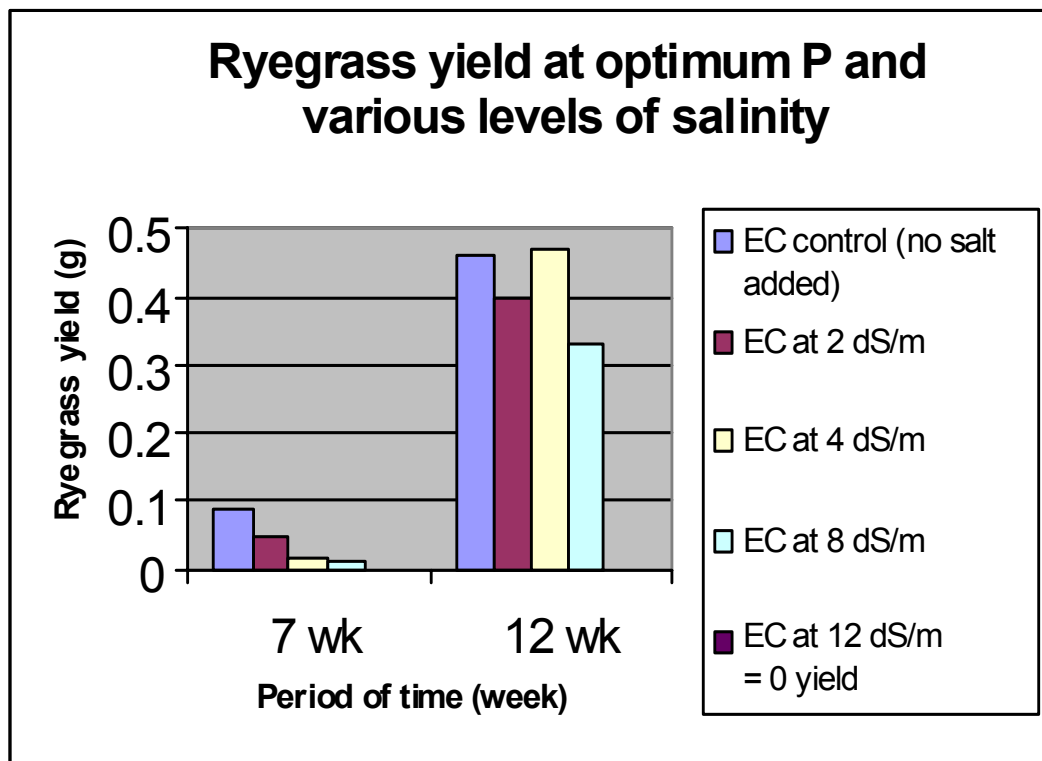


Figure 4.25. Ryegrass yields at 5 levels of salinity at 2 different harvest periods.

Reductions in yields in both harvests indicated that plant growth was adversely affected by increasing salinity leading to yield reduction. Similar observations were found in plants grown in saline conditions (Marcar et al., 1999). Unsatisfactory plant growth may result from inhibited or reduced physiological functions of plant, inadequate moisture, poor physical condition of the soil, other chemical properties and nutritional inadequacy, interference or imbalance (Luken, 1962; Bains and Fireman, 1968). However, in this present experiment, soil conditions and nutritional inadequacies should not have been controlling factors, so the impact of salt on plant physiological functions would appear the most likely control. A similar response was found in cotton and corn in greenhouse studies by Khalil et al. (1967). However, Maas (1986) found that the salinity threshold for ryegrass was at 5.6 dS/m, this level of salinity progressively decreased the final size of plants and yield.

Mineral compositions of the ryegrass plant tissues are shown in **Table 4.13**. At constant P (25 ppm), P tissue content in ryegrass harvested after 7 weeks decreased gradually as salinity level increased. Apart from the control, a similar trend for P tissue content was also found in the final harvest.

These data indicate that P content in plants was depressed by salinity. The adverse effect of salt was, most likely, a reduction in the capacity of plants to uptake nutrients, especially P. Other researchers have also observed that salt inhibits P absorption by plants or influences plant physiology to reduce the P uptake (Fine and Carson, 1954; Moukhtar et al., 1974; Manchanda et al., 1992). Fine and Carson (1954) found that Na salt additions decreased yields and P uptake in barley and oats in greenhouse experiments, while Greenway (1962b) showed reduced P transport and uptake in tomato. Gauch and Eaton (1942) observed the P content of bean leaves and stems tended to decrease with increasing salinity. Moukhtar et al. (1974) reported

that the depressive influence of NaCl, at relatively high concentrations, was possibly due to an antagonistic effect between Cl and P. The observations of Cl reduced P absorption were also found in barley and sunflower (Zhukovskaya, 1973). Ravikovitch and Yoles (1971) reported that increasing NaCl salinity levels depressed the P content of clover as well as its yield.

Table 4.13. Mineral compositions in ryegrass grown under optimum P and different salinity conditions.

Mineral content	Harvesting duration (weeks)							
	7				12			
	Salinity (EC, dS/m)				Salinity (EC, dS/m)			
	0	2	4	8	0	2	4	8
P (%)	0.33	0.31	0.25	0.23	0.11	0.15	0.14	0.11
Cl (%)	NA	NA	NA	NA	1.7	1.6	1.3	2.0
Na (%)	0.64	2.1*	0.82	0.75	0.44	0.35	0.15	0.65
Ca (%)	2.8	4.1	17*	6.4	2.8	2.5	5.2	3.0
Mg (%)	0.33	0.26	0.26	0.20	0.37	0.33	0.30	0.33
K (%)	3.5	3.1	2.3	2.1	2.8	4.3	3.9	2.7
S (%)	0.36	0.40	0.23	0.22	0.32	0.42	0.35	0.31
Al (mg/kg)	390	185	135	530	220	115	490	340
Fe (mg/kg)	2200	620	750	810	820	360	1760	700
Mn (mg/kg)	41	43	35	31	69	55	50	39
Cd (mg/kg)	<0.9	<1	<2	<9	1.0	1.4	<0.5	0.84
Cu (mg/kg)	159	52	65	48	46	44	126	56
Mo (mg/kg)	<2	<3	<4	<20	2.0	2.7	2.9	2.0
Co (mg/kg)	<2	<3	<3	<20	<0.9	<0.9	<1	<0.9
Ni (mg/kg)	6.4	5.7	<5	59	4.7	3.3	5.8	6.5
Zn (mg/kg)	89	64	44	37	44	57	99	52

Note : NA= not available due to plant tissue was insufficient for analysis

* = Values considered in error

Comparing the tissue P contents between the first and second harvests, the second harvest P contents were markedly lower in all treatments. This indicates that the concentration of P diminished over time as plants developed. Plant roots absorb phosphate much more rapidly when the plants are young than do the roots of older plants. As plants get larger and take up little extra P, total P in plant remains about the same, but the concentration per unit mass decreases. Plank (1999) noted that the P content of plants is initially high and declines with age. Therefore, during early plant growth stages, the concentration of P is critical (Wright et al., 1984).

Due to insufficient amounts of plant material, the Cl content in plant tissue could not be measured in the first harvest and was only determined after 12 weeks. The highest Cl content (2%) was detected at highest at salinity of 8 dS/m together with the lowest yield. Similar findings have been found in corn and tomato (Patel and Wallace, 1976).

The present results also indicated that macronutrients like K, Mg and S in plant tissues tended to decrease as salinity increased after the first 7 weeks. Micronutrients such as Cu and Zn in plant tissues, also showed decrease with increasing salinity after the first 7 weeks. The same pattern was also found for Mn, but for both 7 and 12 week growth. Other mineral contents such as Al, Cd, Co, Fe and Ni did not show any pattern. The same observations were found in *Salicornia rubra* in greenhouse study, where Na and Cl contents of plants increase with an increase in salinity, while Mg and K contents decreased (Khan et al., 2001).

Considering the satisfactory values for mineral contents in plant tissue as found in literature (**Table 4.11**), ryegrass in this study, showed sufficient P content after the first 7 weeks (0.23-0.33%), but after 12 weeks, plant P content had reduced dramatically, reaching the deficiency range. Na, Ca and Cl contents in plant tissues

in this experiment were found to be high compared to sufficiency requirements. The sufficiency Na range is between 0.01 and 0.04 %, with a concentration of 0.5% of plant dry weight causing toxic symptoms (Yaron et al., 1973). The Na content in this study was found higher than sufficient ranges and toxicity values especially for the first 7 weeks. Yaron et al. (1973) reported that the Cl sufficiency range in plant tissue was at 0.5-1.8%, on a dry weight basis. This study has shown the Cl content in the tissues to be above the sufficiency range. The Mg content in plant tissue was found to be sufficient for plant growth. The S and Mn contents in plants were deficient, especially during the first 7 weeks, and at high salinity levels (4 and 8 dS/m). The Cu, Mo and Zn contents were found to be higher than the sufficiency values. The K was the only element that remained in the sufficiency range for both growth periods.

In this study, visible injury in ryegrass was observed during the first 7 weeks as the salinity increased. Salinity levels ranging between 4 and 8 dS/m produced the symptoms of stunted growth, yellowing, tip burn and plant fatality, and at salinity 12 dS/m, no seeds germinated. Similar observations were found by Yaron et al. (1973) and Poljakoff-Mayber and Gale (1975). They found the same physical appearance especially in younger plants. These observations were confirmed by the high Na and Ca contents and the reductions of K and S contents in plant tissues during the first 7 weeks.

Visible injuries, such as, leaf necrosis were still observed during the later period of growth, but affected the plants less compared to the first 7 weeks. The symptoms may arise from high Cl content in plant tissue; Balba (1995) observed similar symptoms of leaf burn at the leaf margins due to chloride accumulation causing toxicity. Yaron et al. (1973) suggested that the critical chloride concentration in plant tissue is in the range of 0.5-1.8% for sensitive plants to present leaf injury, while

tolerant plants can accumulate up to 4% without injury. Gausman et al. (1958) and Karmarkor and Joshi (1969) also suggested that chloride, up to certain limits, was essential for plant nutrition through the phosphorelation process, but, adverse effects were expected at high levels.

Figure 4.25 shows that plant growth was affected by salinity more severely in the early stages (comparing yields after 7 weeks and after 12 weeks). It appears that the salinity impacts vary during the plant growth cycle. As plants grew older, their salt tolerance appeared to improve, showing more tolerance to salinity as they reached maturity. Growth of ryegrass is shown in **Figure 4.26**. Other researchers have noted that older plants are more tolerant to salt affected soils than younger ones (Ravikovitch and Porath, 1967; Maas and Hoffman, 1977); some plants are sensitive during germination, while some plants are salt tolerant during later stages of growth. For plants in saline soils, growth was distinctly retarded during germination, but, as the plants grew older, their salt tolerance improved.

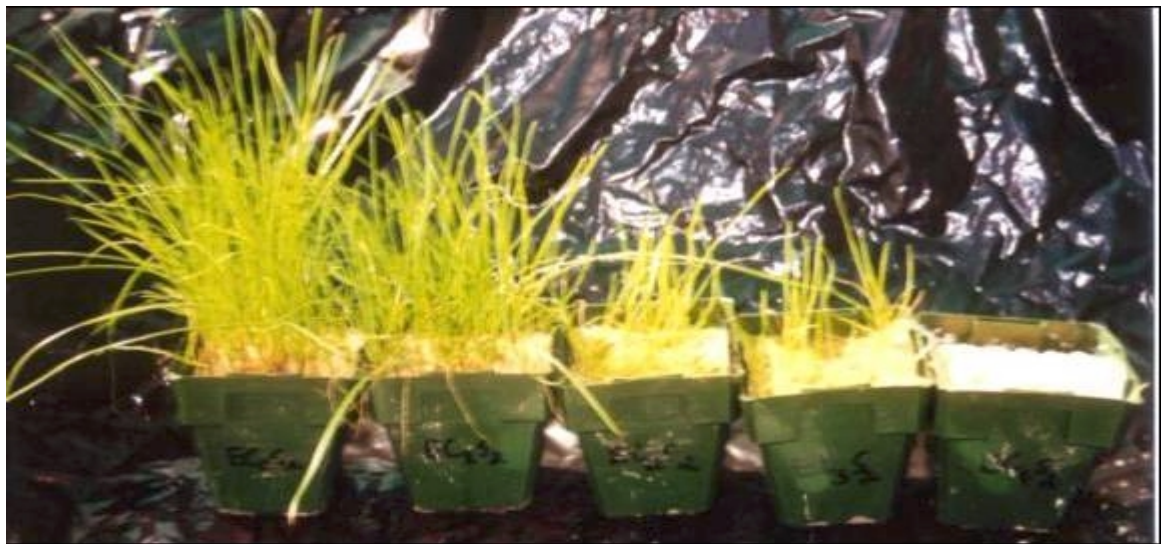


Figure 4.26. Morphology of ryegrass at 5 levels of salinity at optimum P (from left to right, the pots contain salinity at 0, 2, 4, 8 and 12 dS/m).

There are many factors influencing salt tolerance of plants including plant, soil, water and environmental variables, such as plant physiological constitution, the stage of development, and rooting habits (Maas and Hoffman, 1977). Ryegrass is considered moderately salt tolerant, with the ability to tolerate up to 8 dS/m (Maas, 1986; Maas and Hoffman, 1977). The insignificant reduction in yield after maturity in salinities up to 8 dS/m was almost certainly due to its ability to withstand the effects of salt.

In conclusion, salinity affects ryegrass at all stages of growth even when optimal P was provided. Ryegrass plants, however, became increasingly more tolerant with maturation. P content in tissues tended to decrease as salinity increased. Salinity affected the P uptake by plants. This experiment also indicated that ryegrass absorbed more P in the early stages of growth and the P was used in the development until plants were mature.

4.7 Investigation of Salinity and P Interactions in Pot Experiments where 2 Salinity and 5 P Levels were Used

As described in **Section 3.10.3**, a pot experiment was set up involving growth of 4 species at 2 salinity levels (control and 4 dS/m) with various levels of P solution application (3, 10, 17, 25 and 35 ppm as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$). The aims of this experiment were to observe yield of plants and plant features under various levels of P concentration and 2 constant levels of salinity. Yields of plants are reported in **Figures 4.27, 4.28, 4.29, and 4.30**.

In general, plants grown in non-saline cultures had greater fresh and dry weights than in saline conditions. Yields in non-saline treatments increased with added P to

25 ppm. At the lowest P addition (3 ppm), plants produced lower yields for both non-saline and saline treatments, suggesting that 3 ppm P was an inadequate concentration for plants, leading to lowest yield. An increase in salinity at 4 dS/m caused yield reduction in all treatments (except in orchard grass) at the same P addition when compared to controls (no salinity imposition). The salinity effects on yields were more clearly observed at higher P levels (above 3 ppm). This observation was in agreement with Khalil et al. (1967) that absolute differences in yield due to salinity were relatively small for the non-fertilised (low nutrition) treatments and increased with the fertiliser application. They suggested that the decreased yields were due to the detrimental effects of salt. Similar results were observed in plants where excessive amounts of salt caused injury and salt disturbed plant nutrition, its metabolism and prevented water uptake (Throne and Peterson, 1954; Bernstein et al., 1974; Pojakoff-Mayber and Gale, 1975). The following paragraphs present the results and discuss each studied plant. Plant mineral contents were compared to the sufficiency requirements as shown previously in **Table 4.11**.

Figure 4.27 presents the red clover yield data. Red clover showed no significant increase in yield above 17 ppm P without salinity addition, but when salt was added (4 dS/m), plants responded favourably to higher P (25ppm). Phosphorus addition higher than 25 ppm did not increase red clover yield in both non-saline and saline treatments. In all the treatments, salt reduced plant yields. McLaren and Cameron (1996) indicated that red clover is a salt sensitive species, i.e., its yield would be reduced due to the sensitivity to salinity.

Table 4.14 shows mineral compositions in red clover tissue. Phosphorus content in red clover tissue tended to increase when added P was increased in both

non-saline and saline treatments. The Cl and Na contents in plant tissue tended to be higher in saline treatments compared to non-saline ones. The S content in plant tissues increased slightly for both non-saline and saline treatments as added P increased. Salinity had no effect on S tissue content. The Cd content was relatively constant with increasing added P for both treatments. There was no clear pattern found for Ca and other trace elements in plant tissues.

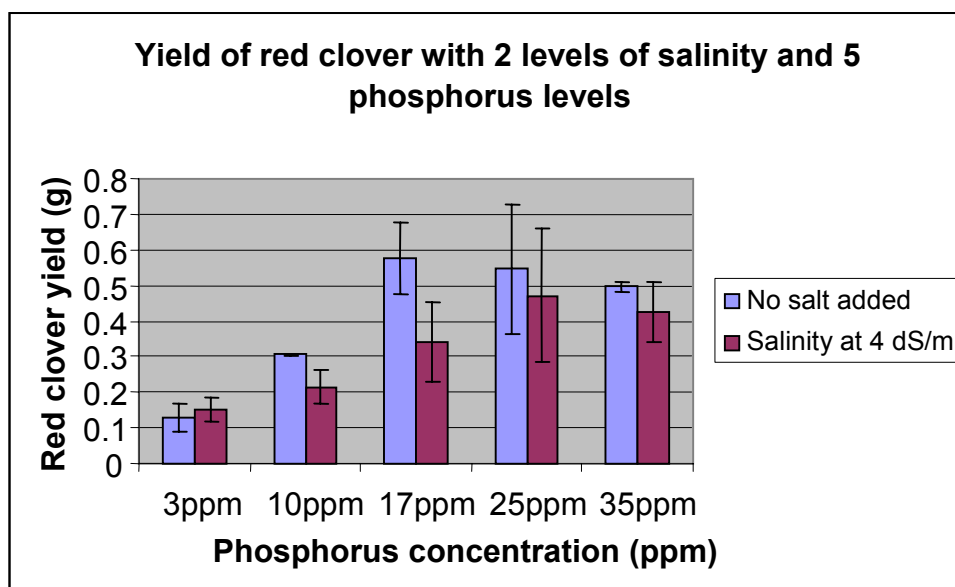


Figure 4.27. Yield of red clover at 2 levels of salinity and 5 levels of P.

Comparison between concentrations of selected elements in experimental plant tissues and the literature for healthy plants (see **Table 4.11**) reveals that red clover with added P from 17 to 35 ppm in non-saline and saline treatments showed a sufficient amount of P in the tissue (sufficiency range is between 0.2-0.3%). The Cl, Ca and K contents were higher than plant requirements, especially Cl content in saline treatments, which reached the toxicity level (0.5%). Mg content was sufficient

for all treatments, whereas S content at higher than 17 ppm added P showed sufficiency values.

Table 4.14. Mineral contents in red clover grown at different levels of salinity and P.

Plant mineral contents in red clover	Control (no salt addition)					Salinity at 4 dS/m				
	P level (ppm)					P level (ppm)				
	3	10	17	25	35	3	10	17	25	35
P (%)	0.08	0.14	0.25	0.29	0.30	0.08	0.15	0.23	0.24	0.32
Cl (%)	0.38	0.69	0.88	1.2	0.44	1.2	2.0	1.4	1.3	2.3
Na (%)	0.043	0.15	0.12	0.14	0.028	0.35	0.46	0.28	0.27	0.45
Ca (%)	3.8	3.1	2.9	1.83	2.10	4.9	2.3	1.96	2.4	2.2
Mg (%)	0.28	0.28	0.33	0.35	0.32	0.24	0.35	0.35	0.32	0.33
K (%)	2.7	3.3	3.7	4.3	4.2	2.3	3.5	4.3	3.8	4.8
S (%)	0.14	0.16	0.20	0.22	0.23	0.13	0.20	0.22	0.20	0.24
Al (mg/kg)	100	220	109	113	94	167	147	187	138	103
Fe (mg/kg)	450	710	460	380	610	940	810	950	610	250
Mn (mg/kg)	117	116	87	94	104	195	143	160	108	71
Cd (mg/kg)	<0.9	<0.4	<0.4	<0.4	<0.4	<0.8	<0.4	<0.4	<0.4	<0.4
Cu (mg/kg)	11	20	16	16	19	20	22	29	19	14
Mo (mg/kg)	7.3	11	16	10	7.7	3.5	4.9	8.3	8.0	9.4
Co (mg/kg)	3.7	<0.9	<0.9	<0.9	<0.9	<2	1.2	1.0	<0.9	<0.9
Ni (mg/kg)	<3	3.8	4.6	3.1	3.4	4.6	4.3	9.3	4.0	1.8
Zn (mg/kg)	230	161	135	171	136	230	260	165	150	147

Birdsfoot trefoil yield data is presented in **Figure 4.28**. There was very high variation in yields in all treatments. The results showed insignificant differences among yields at any levels of P additions except at 3 and 35 ppm in saline treatments, where yield was higher when P was added at 35 ppm. Salt reduced plant yields and

increasing P above 17 ppm reduced plant yield in saline conditions. However, yields in non-saline treatments tended to increase as added P increased and the highest yield was obtained at 35 ppm added P.

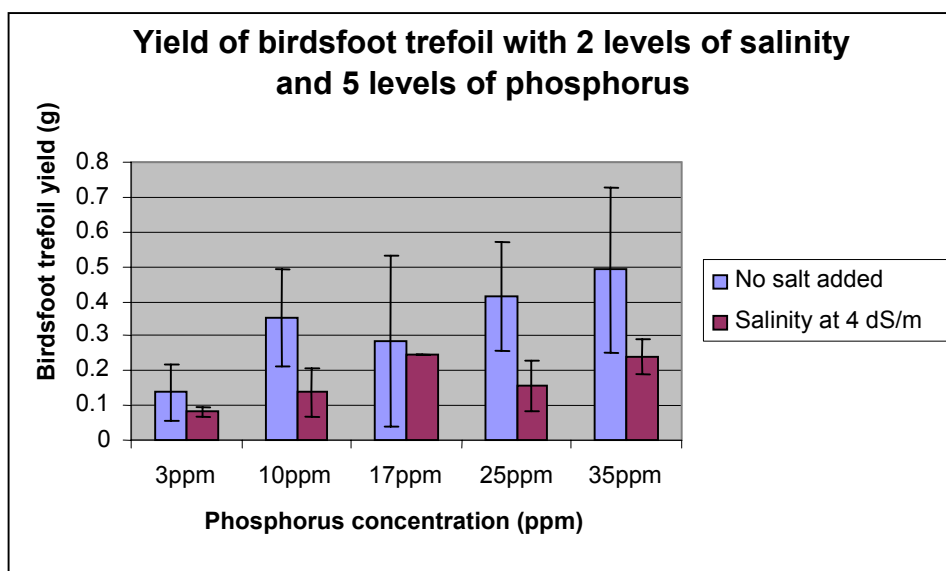


Figure 4.28. Yield of birdsfoot trefoil at 2 levels of salinity and 5 levels of P.

Table 4.15 presents plant tissue element contents in birdsfoot trefoil. High Na and Cl contents were found in the tissues for plants grown in 4 dS/m. Phosphorus tissue contents were higher in saline treatments compared to non-saline ones, but was not related to added P concentration. The Ca content decreased slightly when added P increased in non-saline treatments. The Mg content tended to be relatively constant in the plant tissues. Salinity seemed to increase some internal mineral contents in the plant tissues, such as Cl, Na, Ca and S but lower some trace elements, such as Al, Fe and Mn contents.

From **Table 4.11**, birdsfoot trefoil requires approximately 0.20-0.30% P in the tissues. This study showed that sufficient P content in plant tissues was found at 17 ppm added P for both saline and non-saline treatments. The K, S and Mg contents were at sufficient levels for plant growth, while Ca, Na and Cl contents were higher

than sufficiency ranges, especially in saline pots. High amounts of trace elements, such as Cu, Fe, Mn and Zn were found in plant tissues.

Table 4.15. Mineral contents in birdsfoot trefoil at different levels of salinity and P.

Plant mineral contents in Birdsfoot trefoil	No salt addition					Salinity at 4 dS/m				
	P level (ppm)					P level (ppm)				
	3	10	17	25	35	3	10	17	25	35
P (%)	0.12	0.21	0.27	0.11	0.22	0.12	0.16	0.25	0.36	0.32
Cl (%)	NA	1.7	0.56	0.58	0.82	NA	1.5	1.3	2.0	NA
Na (%)	0.06	0.62	0.1	0.05	0.13	0.39	0.39	0.38	0.75	0.65
Ca (%)	4.6	2.3	1.69	1.37	0.68	2.5	3.5	5.2	3.7	3.4
Mg (%)	0.2	0.3	0.19	0.31	0.28	0.2	0.2	0.29	0.25	0.22
K (%)	2.3	4.9	4.0	4.0	4.5	2.8	4.1	4.8	4.8	4.2
S (%)	0.15	0.27	0.25	0.21	0.24	0.23	0.22	0.28	0.29	0.26
Al (mg/kg)	340	52	480	220	400	200	118	61	76	81
Fe (mg/kg)	1460	210	1110	670	2700	680	370	260	320	350
Mn (mg/kg)	138	68	146	93	96	75	56	51	72	67
Cd (mg/kg)	<1	<0.4	<0.5	<0.4	<0.4	<2	<0.9	<0.4	<0.9	<2
Cu (mg/kg)	26	11	26	17	26	13	8.4	11	11	9.5
Mo (mg/kg)	4.0	8.9	10	4.5	8.7	4.2	7.8	6.8	7.6	5.3
Co (mg/kg)	<2	<0.9	2.2	<0.9	1.2	<4	<2	<0.9	<2	<5
Ni (mg/kg)	18	1.6	6.7	3.4	35	11	3.2	2.0	3.2	<7
Zn (mg/kg)	96	174	97	173	172	113	123	124	118	101

Figure 4.29 shows orchard grass yield data. There was high variability in yields. Salt did not reduce plant yield. Best growth was observed at 35 ppm added P for both no salt and salt treatments. Added P increased plant yields in both treatments.

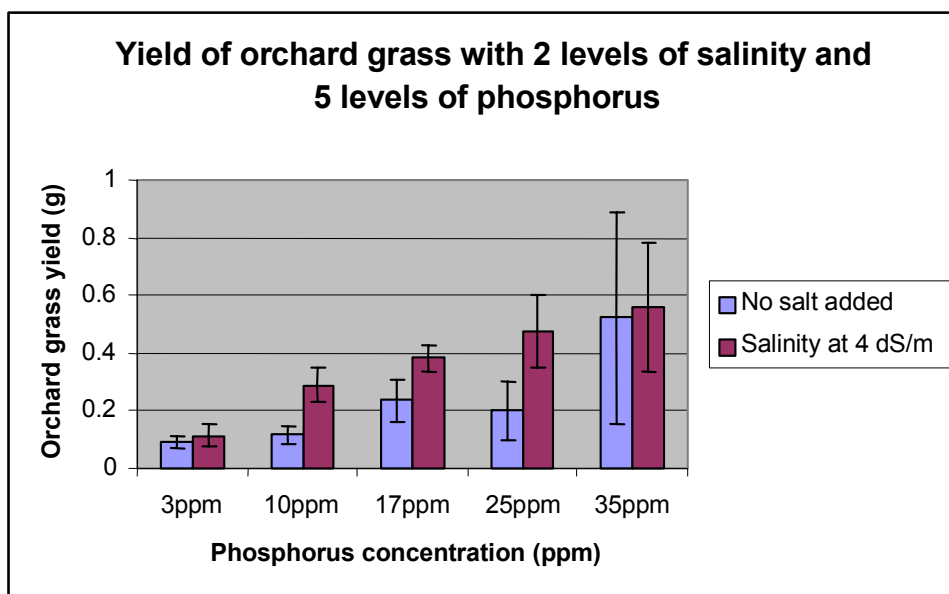


Figure 4.29. Yield of orchard grass at 2 levels of salinity and 5 levels of P.

Table 4.16 presents data on mineral contents in orchard grass tissues. Phosphorus content increased when added P increased for both non-saline and saline treatments. There was an insufficient material for Cl analysis for the no salt treatments, but with saline treatments, when added P was increased, Cl content tended to increase. The Ca content was higher in saline treatments compared to non-saline treatments (Ca content at 3 ppm added P in control treatment was relatively high). Other elements did not show any patterns of quantity with added P or salinity.

From **Table 4.11**, satisfactory growth requires 0.25-0.35% P during vegetative growth. Based on this P concentration range, P content in orchard grass was found to be sufficient for growth above 17 ppm added P in non-saline treatments and at 25 and 35 ppm added P in saline treatments. Mg and S contents in plant tissues were in the adequate ranges, while Ca content was excessive. The K content in plant tissues was sufficient when P was added at 3 ppm for both treatments, but

was in excess at other added P levels. High Cl content was found in plant tissues, while the Na content in the tissue was found to be at toxic levels in saline treatments for all added P concentrations. Trace elements were within the sufficient range.

Table 4.16. Mineral contents in orchard grass at different levels of salinity and P.

Plant mineral contents in orchard grass	Control (no salt addition)					Salinity at 4 dS/m				
	P level (ppm)					P level (ppm)				
	3	10	17	25	35	3	10	17	25	35
P (%)	0.05	0.12	0.24	0.24	0.29	0.08	0.16	0.18	0.28	0.28
Cl (%)	NA	NA	NA	1.0	NA	NA	0.98	0.95	1.1	1.2
Na (%)	0.08	0.14	0.08	0.11	0.24	0.47	0.94	0.78	1.25	0.64
Ca (%)	11.2	4.9	1.85	1.3	1.5	8.3	1.6	6.6	4.4	3.4
Mg (%)	0.16	0.22	0.18	0.24	0.22	0.18	0.20	0.23	0.26	0.24
K (%)	2.3	4.5	6.4	7.1	6.5	2.5	5.0	5.3	5.5	4.7
S (%)	0.14	0.3	0.36	0.41	0.33	0.28	0.41	0.37	0.42	0.30
Al (mg/kg)	67	48	35	30	65	106	30	28	23	300
Fe (mg/kg)	220	270	194	98	350	730	200	108	141	820
Mn (mg/kg)	108	220	152	135	109	360	280	154	169	108
Cd (mg/kg)	<3	<3	<1	<0.9	<0.9	<2	<0.7	<0.5	<0.4	<0.4
Cu (mg/kg)	<9	19	14	16	19	30	20	20	19	19
Mo (mg/kg)	<8	<6	3.1	3.4	4.8	<5	6.6	5.9	4.1	9.4
Co (mg/kg)	<8	<6	<3	<2	<2	8.8	<2	<1	<0.9	<0.9
Ni (mg/kg)	<10	<8	<4	7.9	3.2	9.6	4.7	6.7	4.8	8.0
Zn (mg/kg)	71	220	173	230	177	139	290	280	320	160

Note: NA= not available due to plant tissue was insufficient for analysis

Ryegrass yield results are shown in **Figure 4.30**. Ryegrass produced the best yield at 35 ppm in the no salt treatment and 17 ppm in salt treatment. Salinity tended

to decrease yields but insignificantly. The insignificant yield reduction may be because ryegrass is a moderate-salt tolerant species and has the ability to tolerate high salinity (6-8 dS/m with 50% yield damage at EC of 12.2 dS/m) (Follet et al., 1981; Peverill et al., 1999). There was no significant difference in yield at any added P level (10-35 ppm) when yields were compared between non-saline and saline treatments. The P additions above 17 ppm did not improve plant yields.

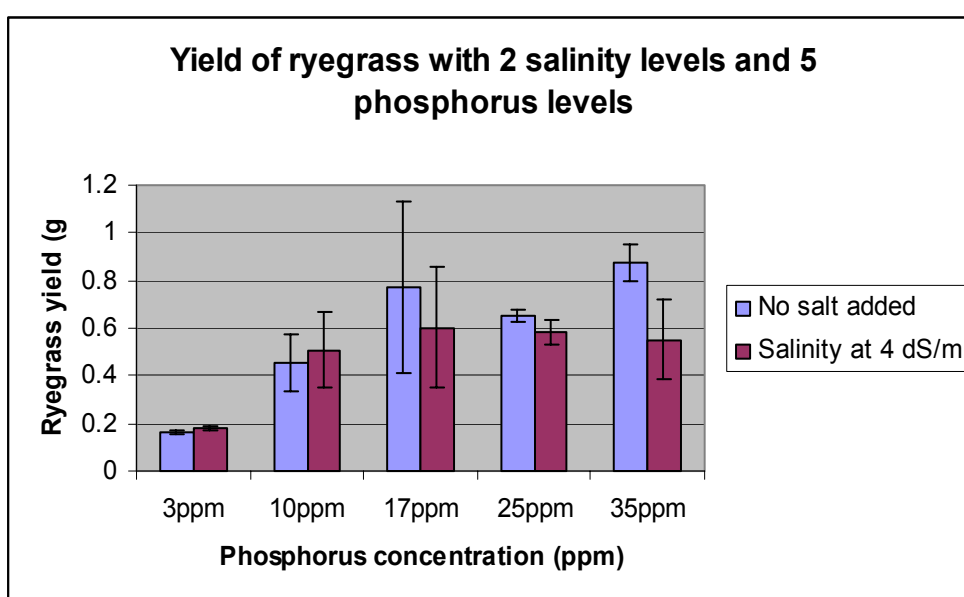


Figure 4.30. Yield of ryegrass at 2 levels of salinity and 5 levels of P.

Table 4.17 shows mineral compositions in ryegrass. The P content in ryegrass tissue in non-saline treatments was increased when added P increased. Similar observations were also found in saline treatments, but, the P contents of plants were higher. The Cl and Na contents in plant tissue also increased with increasing added P. Among the plants studied, ryegrass absorbed the highest Cl (3.4%) in tissues (compared to, e.g., red clover, which had the lowest level of 0.38% Cl). The Ca and Mg contents did not show any clear patterns when added P or salinity were increased. There was an increase in Cu content in plant tissues in non-

saline and saline treatments as added P increased. The S content also increased with added P, but only in non-saline treatments.

Table 4.17. Mineral contents in ryegrass at different levels of salinity and P.

Plant mineral contents in ryegrass	Control (no salt addition)					Salinity at 4 dS/m				
	P level (ppm)					P level (ppm)				
	3	10	17	25	35	3	10	17	25	35
P (%)	0.06	0.09	0.11	0.13	0.16	0.07	0.12	0.20	0.16	0.23
Cl (%)	1.1	1.4	1.4	2.2	2.2	1.2	1.7	2.7	2.9	3.4
Na (%)	0.30	0.20	0.25	0.40	0.54	0.93	1.34	1.55	1.37	1.57
Ca (%)	4.9	1.95	0.77	1.46	0.67	6.3	1.3	1.0	2.6	1.3
Mg (%)	0.15	0.19	0.18	0.24	0.22	0.18	0.20	0.23	0.26	0.24
K (%)	2.9	4.5	3.9	4.4	4.1	2.5	4.0	4.3	3.9	4.2
S (%)	0.23	0.24	0.24	0.27	0.27	0.30	0.31	0.35	0.27	0.32
Al (mg/kg)	350	31	64	106	350	77	71	87	76	56
Fe (mg/kg)	440	138	310	250	650	210	210	270	280	240
Mn (mg/kg)	160	137	90	91	109	181	152	106	107	108
Cd (mg/kg)	<0.7	<0.4	<0.4	<0.4	<0.4	<0.8	<0.4	<0.4	<0.4	<0.4
Cu (mg/kg)	17	14	18	20	25	18	20	21	21	20
Mo (mg/kg)	7.0	6.5	5.3	6.3	4.3	2.8	7.8	5.0	4.9	5.6
Co (mg/kg)	<2	<0.9	<0.8	<0.9	<0.9	<2	<0.9	<0.9	<0.9	<0.9
Ni (mg/kg)	5.5	5.2	13	5.8	9.6	<3	4.1	4.0	8.7	4.8
Zn (mg/kg)	166	210	180	230	210	163	240	250	210	260

Optimum P requirements in ryegrass plants are 0.2-0.4% P during their growth (**Table 4.11**). Based on these values, P contents in this experiment appeared to limit plant growth. Only in saline treatments where added P was from 17 to 35 ppm did ryegrass plants have sufficient P. Other elements, i.e., Ca, Na, and Cl, were

found in excess of the optimum requirements, where salinity was imposed. The S content in the tissues was within sufficiency range when salinity was imposed.

Generally, the observations on plant tissue mineral contents in relation to salinity indicated that there was higher P content in tissues in saline treatments when compared to non-saline treatments at the same level of added P. Similar observations were found in experiments using an artificial salinised soil in the greenhouse where the P absorption by barley plants was related to the salt concentration (Ferguson and Hedlin, 1963). In that study, P absorption increased with increasing salt concentration until it reached a maximum at EC of 6 dS/m, and then declined with further increase in salt concentration. Solution culture studies also revealed the same relationship between salt concentration and P absorption in barley (Awad et al., 1990). This finding was attributed to the effect of salts on the physiology of the plant rather than the effects of salts on P solubility. Moukhtar et al. (1974) also reported that increasing the amount of chloride salt in the root environment, resulted in an increase in the P uptake in plants. Champagnol (1979) found that salinity increased P content in clover, millet, sorghum, maize and sesame. When P was not constant, plants seemed to have the ability to uptake more P at high salinity.

It is possible that plants tried to overcome the effect of salinity by absorbing more P into their tissues. The results of this study also are in accord with data found previously that with added salinity, the plant P concentrations were higher due to reduced growth (Patel et al., 1975). Villora et al. (2000) also reported that increased salinity increased total P accumulation in zucchini.

The enhancement effect of Cl salt on the uptake of P could be explained on the basis of a synergistic phenomenon between Cl and P ions up to certain limits of salt concentration. This has been reported for tomatoes, where P additions slightly

increased Cl content in the leaves (Cerda and Bingham, 1978). In sand culture, high accumulations of Ca, Cl and Na were observed in sorghum where P was added in high concentration at high salinity level (Patel et al., 1975). However, opposite results were obtained in early experiments (**Section 4.6**) in ryegrass, where NaCl reduced P uptake in plants. Therefore, it can be seen that Cl influenced P uptake by plants synergistically and antagonistically.

In this current study, Cl contents in plant tissues increased correspondingly with addition of NaCl to the nutrient solution in all treatments. Ravikovitch and Porath (1967) and Cerda and Bingham (1978), reported that the Cl content of the studied plants rose with increasing soil salinity and its accumulations inhibited plant growth.

Sodium contents in plant tissue also showed a similar trend to Cl and they were related. With the addition of NaCl salt solution, plant tissues tended to show higher Na contents than in non-saline treatments. Bernstein (1964b) suggested that a high concentration of NaCl in saline treatments induced a variety of effects on plant mineral contents. Increases in Na and Cl in plant tissues were found in melon, sesame, millet and clover where NaCl was added (Ravikovitch and Yoles, 1971; Moukhtar et al., 1974; Cerda et al., 1977; Feigin, 1985). A possible explanation lies in the fact that the ability of cell membranes to control salt uptake in plants was reduced by high levels of chloride. Therefore, the contents of Na and Cl are obviously related to the level of salinity in the soil. Cramer et al. (1991) also suggested that ions at high concentrations (e.g., Na or Cl ions from salt addition) were taken up at high rates by plants and led to excessive accumulation in tissues.

Considering the added P in both saline and non-saline treatments in relation to plant tissue contents, increasing P application increased P content in plant tissues in both treatments. Similar results were observed in sesame plant, when increasing the

concentration of added P increased the leaf content of P (Cerdea et al., 1977). In non-saline treatments, when P concentration was increased, no clear pattern was found for Na and Cl contents in the plant tissue. However, in saline treatments, increasing P levels tended to slightly increase Na and Cl in plant tissues. Similar results were observed in tomatoes, where high P treatments increased the Cl uptake (Ravikovitch and Porath, 1967). However, the Ravikovitch and Porath (1967) studies also revealed the opposite results, when a reduction of Cl was found in many crops. In this present study, in some plants, salt did not affect growth markedly, although there were increased accumulations of Na and Cl in the plant tissues. A possible explanation is that adequate P supply leads to the anion balance shifting to more normal conditions, leading to normal growth being obtained (Fine and Carson, 1954).

In conclusion, P additions tended to increase plant yields in normal conditions. Salt reduced plant yields at any P concentration, except for orchard grass, where higher yields were obtained in salt treatments (4 dS/m) compared to the controls (no salt addition). No clear explanation is available for these results. For all treatments, with or without salt, the lowest yield was found at the lowest P concentration (3ppm), the change of yield was insignificant when comparing saline treatments (at 4 dS/m) and non-saline treatments (no salt addition) for all plants studied; i.e., that there was no measurable effect of salinity at low levels of P. Bernstein et al. (1974) noted that with more severely limiting conditions, sensitivity of plants to salinity would be reduced. The interaction between added P and salinity to plants in this study clearly showed that plants responded to P positively with increased P additions in the culture up to specific levels of P. Red clover yield was improved in saline conditions when P solution was added up to 25 ppm, however,

further P additions above 25 ppm reduced yield. Birdsfoot trefoil yield increased slightly when P was added up to 17 ppm in saline conditions similar to ryegrass. Further increases in P decreased and showed no significant change in birdsfoot trefoil and ryegrass yields respectively.

The positive effects of P in saline conditions have been reported widely, i.e., 34 out of 37 crop plants responded positively to P fertilisation at slightly saline conditions when P was raised from deficiency to high level, bean yields in a greenhouse experiment were increased with P at variable salinity levels, and yields of clover and millet were increased by the additions of P and nitrogen (Lunin and Gallatin, 1965b; Ravikovitch and Yoles, 1971; Champagnol, 1979; Feigin, 1985). As discussed earlier, reduction or no significant change in plant yields were observed in this current study as P was added above plant requirements. Similar observations were found in many studies when increasing P fertility decreased yield in saline experiments and also decreased salt tolerance in plants, such as barley, corn and wheat (Schwarz, 1957; Torres and Bingham, 1973; Bernstein et al., 1974; Nieman and Clark, 1976; Maas and Hoffman, 1977) and no significant change in yields of beans and corn when N levels were increased (Lunin and Gallatin, 1965b; Ravikovitch and Yoles, 1971). In contrast to other studied species in this present study, orchard grass presented the best growth at the highest P level (35 ppm) in both non-saline and saline treatments. Optimum P level for orchard grass remained constant in both conditions. Manchanda et al. (1982) observed that barley in greenhouse study had the best growth at highest P level (50 ppm) of added P both on the non-saline control and the CI-treatments.

It can be seen that this current study helps in clarification and understanding the conflicting results reported earlier in the literature that plants responded

differently related to salinity and P. Some workers reported positive results of P towards plant yields in saline conditions, while other researchers indicated negative or no response of plants with P fertility in saline conditions. The contradictions in the literature would likely come from studied range of P. As seen in this current study, plants responded both positively and negatively over the P range in saline conditions. Therefore, when considering plant responses to P in saline conditions, a wide range of P concentrations should be investigated, and the P range should cover suboptimal, optimal and above optimal values.

4.8 Plant Growth in a Naturally Saline Soil with Varying P at Constant Salinity (DP2 Soil)

A natural saline soil, with a known level of P adsorption, was used in this experiment. P was added to the pots after plant establishment (**Section 3.10.4**). Phosphorus levels were varied according to the P maximum adsorption capacity (PMC). Phosphorus was imposed as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ solution at 0 ppm (P0), 0.1 x PMC (P1), 0.25 x PMC (P2), 0.35 x PMC (P3), 0.5 x PMC (P4), 0.7 x PMC (P5), and at PMC (P6). During seed germination, seeds took more than 2 weeks to germinate. Ryegrass took longer for germination than red clover. However, after germination, the ryegrass plants showed better establishment than the red clover (probably because of higher ability to tolerate salt). Salinity has been noted earlier to delay seed germination and maturity (Poljakoff-Mayber and Gale, 1975). Plants were thinned to 10 in each pot after full plant establishment, but, during the experiment, some plants in some treatments died. Dried materials obtained were weighed and as there was insufficient time available to repeat this experiment, an estimate of comparable yields was obtained by multiplying the yield in each pot by 10/ number

of surviving plants. The results of the experiments for calculated yields of 10 plants are presented in **Figures 4.31** and **4.32** for red clover and ryegrass respectively.

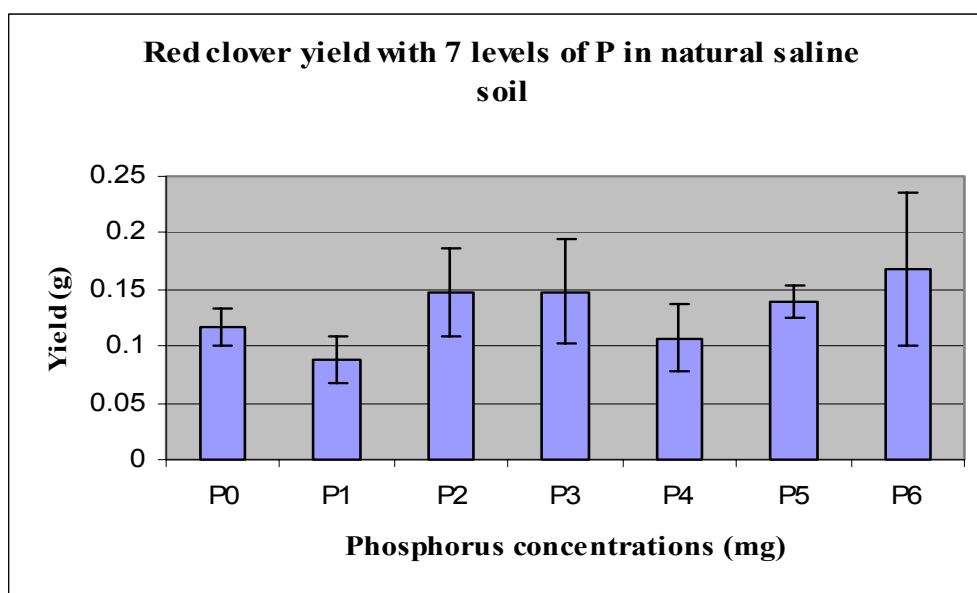


Figure 4.31. Red clover yield in natural saline soil (DP2) with various P levels related to maximum P adsorption capacity.

There was no mass response in yield to P additions in this natural saline soil, i.e., there was no significant pattern in yields with increasing added P. Phosphorus additions in saline soil culture had no visible effect on the plants and yields. Rogers et al. (2003) found similar observations in a greenhouse study where low and high P additions did not affect the lucerne growth under the adverse effect of NaCl. Lunin and Gallatin (1965b) also noted that no significant change in yield was observed in beans and corn when the levels of N fertility were increased in saline environments.

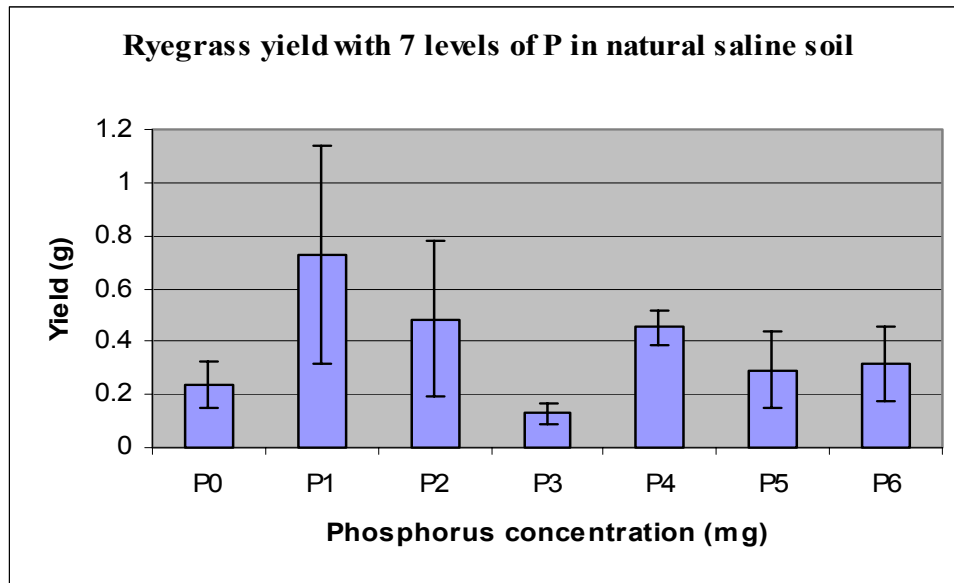


Figure 4.32. Ryegrass yield in natural saline soil (DP2) with various P levels related to maximum P adsorption capacity.

Bains and Fireman (1968) also concluded that the adverse effects of salinity on plants growth are not reduced by fertiliser applications. Rather, a partial response to fertiliser may be expected where nutrient deficiencies limit growth more than salt does. Bernstein et al. (1974) indicated that when ambient salinity is the dominant limiting factor, increasing fertility will be relatively ineffective compared to decreasing salinity. Troeh and Thompson (1993) also suggested that high salt concentrations reduced the response of grain and vegetable crops to fertiliser applications. Everardo et al. (1975) noted that salts in excessive amounts caused substantial changes in the morphology and physiology of plants. The effects of salts on plant growth led to decreased availability of water to plants, inhibiting growth of plants because of an excess of solutes taken up by plants through the toxicity of one or more specific ions present in higher relative concentrations.

Yields in this current study were obtained during a winter planting, therefore, they were less than half those of previous experiments where plants were grown in spring and late summer. Ryegrass produced higher yields than red clover, presumably, because ryegrass is a moderate salt tolerant species (Hannaway et al., 1999). Red clover, on the other hand, grows very slowly in winter and also is a salt sensitive species (Dymock, 1978).

The quantities of dried matter obtained were insufficient for chloride analysis.

Tables 4.18, 4.19, 4.20, 4.21, 4.22, 4.23 and 4.24 present selected mineral contents in dried biomass of red clover and ryegrass at different levels of P addition.

Table 4.18. P and Na contents in red clover and ryegrass tissues from pot experiments conducted with natural saline soil (DP2).

Plant	Plant mineral composition													
	P (%)							Na (%)						
	P0	P1	P2	P3	P4	P5	P6	P0	P1	P2	P3	P4	P5	P6
Red clover	0.20	0.28	0.38	0.42	0.54	0.38	0.41	2.25	2.30	1.76	1.94	2.20	2.40	2.20
Ryegrass	0.18	0.25	0.35	0.43	0.43	0.42	0.46	1.92	2.10	2.45	3.20	3.25	2.70	3.05

Table 4.19. Ca and Mg contents in red clover and ryegrass tissues from pot experiments conducted with natural saline soil (DP2).

Plant	Plant mineral composition													
	Ca (%)							Mg (%)						
	P0	P1	P2	P3	P4	P5	P6	P0	P1	P2	P3	P4	P5	P6
Red clover	4.45	5.50	3.75	5.20	5.20	4.75	4.75	0.96	1.14	1.11	1.01	1.12	1.05	1.00
Ryegrass	1.89	1.56	2.45	3.40	3.00	2.45	2.36	0.47	0.43	0.53	0.67	0.69	0.54	0.68

Table 4.20. K and S contents in red clover and ryegrass tissues from pot experiments conducted with natural saline soil (DP2).

Plant	Plant mineral composition													
	K (%)							S (%)						
	P0	P1	P2	P3	P4	P5	P6	P0	P1	P2	P3	P4	P5	P6
Red clover	2.20	3.00	3.60	3.50	3.80	3.70	3.40	0.22	0.24	0.29	0.27	0.34	0.27	0.29
Ryegrass	3.70	3.20	3.40	2.90	3.25	3.40	3.25	0.30	0.29	0.31	0.32	0.36	0.33	0.33

Table 4.21. Al and Fe contents in red clover and ryegrass tissues from pot experiments conducted with natural saline soil (DP2).

Plant	Plant mineral composition													
	Al (mg/kg)							Fe (mg/kg)						
	P0	P1	P2	P3	P4	P5	P6	P0	P1	P2	P3	P4	P5	P6
Red clover	199	510	228	240	430	255	275	420	690	370	370	740	455	455
Ryegrass	240	96	310	740	205	375	325	330	187	415	790	460	440	390

Table 4.22. Mn and Cd contents in red clover and ryegrass tissues from pot experiments conducted with natural saline soil (DP2).

Plant	Plant mineral composition													
	Mn (mg/kg)							Cd (mg/kg)						
	P0	P1	P2	P3	P4	P5	P6	P0	P1	P2	P3	P4	P5	P6
Red clover	50	78	55.5	50	63	63	55.5	<1	<1	<0.9	<0.9	<1	<1.5	<0.7
Ryegrass	79	54.5	67	71	55	60	74.5	<0.9	<0.4	<0.9	<0.8	<0.6	<0.6	<0.9

Table 4.23. Cu and Mo contents in red clover and ryegrass tissues from pot experiments conducted with natural saline soil (DP2).

Plant	Plant mineral composition													
	Cu (mg/kg)							Mo (mg/kg)						
	P0	P1	P2	P3	P4	P5	P6	P0	P1	P2	P3	P4	P5	P6
Red clover	11.5	12.0	14.5	16.0	15.0	13.0	12.5	<3	<2	<2	<2	<3	<4	6
Ryegrass	13.0	12.0	15.0	17.0	15.5	15.0	15.5	<2	<0.9	<2	<2	1.1	<2	<2

Table 4.24. Co and Zn contents in red clover and ryegrass tissues from pot experiments conducted with natural saline soil (DP2).

Plant	Plant mineral composition													
	Co (mg/kg)							Zn (mg/kg)						
	P0	P1	P2	P3	P4	P5	P6	P0	P1	P2	P3	P4	P5	P6
Red clover	<3	<2	<2	<2	<3	<3	<2	57	97	96.5	76	187	111	129
Ryegrass	<2	<0.9	<2	<2	<1	<2	<2	77	79.5	103	121	131	86	70

P content in plant tissue was lowest in the control (P concentration at 0 ppm). The highest P content in plants was found at P4 in red clover, while ryegrass gave the highest P content at P6. Yield and P content level were not related. In ryegrass, P content tended to increase as P concentration in soil was increased, while there was no clear correlation between P tissue content and added P in red clover. The Ca, Al and Fe contents were highest at P4 in red clover. The Ca and Na contents in both plant tissues did not show any patterns when added P was increased. The Ca and Mg

contents in plant tissue were found to be higher in red clover than those in ryegrass. Trace elements such as Cd, Mo and Co did not show any significant changes when added P was increased. The effect of P fertilisation on plant contents of Cl and Na and the effect of salinity on plant P content reported elsewhere are very variable and differ between plant species and also environmental conditions (Champagnol, 1979; Feigin, 1985). Champagnol (1979) noted that the effect of salinity on P content in the tissue of different crops varied greatly and the effect of salinity on the concentration of nutrient elements in plant tissue can be explained partially by its effect on plant or population size. High chloride uptake was observed in plants causing plant injury and reduced growth at high salinity treatments. The presence of salt can influence ion uptake by plants and affect their chemical composition (Feigin, 1985).

Comparison between P tissue content and P requirements listed in the literature (see **Table 4.11**) shows that P tissue contents in this experiment were sufficient for plant growth except in ryegrass with no added P. There were high Na tissue contents in both plant species grown in this saline soil at all levels of added P. The Ca, Mg and Fe tissue contents were observed at toxicity levels.

During the experiment, plants were observed regularly. Leaf burn and yellowing were found in ryegrass plants in nearly all treatments except at the higher P treatments (P4, P5 and P6). The injuries may be the result of high levels of Na in tissues. The same visible symptoms were also seen in plants under saline conditions with mottling or spots, leaf curling and incipient chlorosis (yellowing). In severe cases, necrosis and leaf burn occur (Black, 1957; Yaron, et al., 1973). In red clover, thin stems, stunted growth, dark green leaves were found in all treatments except P6.

Soil in experimental pots was also observed and its properties after the experiment were examined. During the experiment, soil was found to be very compact showing waterlogged conditions on the surface after wetting. However, water drained slowly to the bottom. Therefore, waterlogging may have been a temporary problem in some pots due to slow movement of water from the soil surface downwards. These waterlogged conditions are often found in natural saline environments. Kingwell (2003) noted that high concentrations of salt are often accompanied by waterlogged conditions. Such conditions on the surface limit gaseous diffusion, cause nutrition problems, and also increase phosphorus sorption capacity in soil. Marcar and Khanna (1997) noted that in a saline soil, there is high ratio of Na and Ca compared to other cations. For this present study, it is possible that some ion species in DP2 soil may be complexing P and rendering it less available, but no data on such reactions was available.

Due to poor soil structure, plants grown in the soil in this experiment may have suffered from poor physical conditions in the pots, which contributed to the lack of response to added P, leading to low yields. Root distribution of plants was found to be close to the surface, especially with red clover, where the roots did not go below the middle of the pots. Ryegrass roots penetrated deeper through the soil than red clover roots and showed greater root distribution. Plants were observed to struggle in this saline environment, especially with salinity causing soil properties unfavourable for plants. Thorne and Peterson (1954) suggested that plants in saline environments have to withstand poor aeration in waterlogged conditions, in addition to their ability to deal with relatively high concentrations of salts leading to low yields.

Red clover uptook high quantities of Mg and Na; these elements were at toxic levels. This feature has been noted by Thorne and Peterson (1954) who suggested that Mg is more toxic than Na and Ca.

Soil in each pot was analysed for pH, EC and available P. pH varied between 7.31 and 8.60. Soil pH at the bottom of the pots was slightly higher than that of the topsoil. The EC was slightly higher at the topsoil than that of the bottom soil. The EC after the experiment was slightly higher than before the experiment (possibly due to added nutrient solutions). Available P was slightly lower at the top part of the pot compared to the lower part.

In summary, salinity affected seed germination and plant growth. Poor soil structure and high salinity resulted in unsuitable conditions for plants. Plants struggled to survive in conditions where the soil became compact and waterlogged in the surface at times. The Mg, Ca and Na contents in plants reached toxicity levels and these may be related to high quantities in the soil. Excessive mineral uptake by plants induced by saline conditions resulted in insignificant yield responses. Bains and Fireman (1968) and Feigin (1985) suggested that plant growth was adversely affected by high salinity and the unsatisfactory growth resulted from reduced physiological functions or disorders of plants, poor physical conditions of the soil and nutritional effects. These present results are attributed to the effects of salt on the plant physiology rather than the effect of salt on phosphorus solubility. Similar observations were found in barley plants in the greenhouse study by Ferguson and Hedlin (1963).

Insignificant change in plant yields regarding to salinity and P in this study was in agreement with observations elsewhere, (i.e., Feigin, 1985; Papadopoulos and Rendig, 1983) that when N levels were increased, no significant change in yield was observed in corn and beans, and increasing N levels in nutrients solutions from 8 to 64 mg/L and 120 mg/L resulted in a positive yield response in tomato plants growing in low-salinity soil (1 dS/m); however, no yield increase due to N application was found when the similar level was 5 dS/m or more than 9 dS/m.

This current study suggests that inconsistent results (positive, negative, or no significant change) regarding to interactive effects between salinity and fertility reported earlier in the literature were likely to have arisen from having used different degrees of salinity. Some plants respond to added fertility at low and medium levels of salinity (both positive and negative), while at high levels of salinity, no response to fertilisation application is likely to be obtained. Therefore, to observe the interaction between salinity and fertility, wide ranges of salinity should be included (see recommendations in **Section 5.3**).

4.9 Limitations of this study

This study had a number of limitations that may have contributed to the results not producing outright conclusions.

There was no controlled temperature and humidity glasshouse available, thus preventing accurate comparisons between different experiments. Yields of plants were influenced by the varying temperature conditions and thus comparison of yields for the same species in different experiments was not possible.

There was a limitation in time for each experiment. Plants were grown in pots for 12 weeks for all experiments in summer and winter climates. In general, there

was no opportunity for time compensation for winter growth, although longer times for germination and plant establishment were utilised. Two experiments were also impacted by external factors; in one, birds got into the glasshouse and damaged numerous pots leading to abandonment of the experiment after 8 weeks. In another experiment, a windstorm severely damaged the glasshouse at the end of the experiment (after plant harvest), before pot sand samples could be separated for post-experiment analyses (the pots were blown over and samples mixed). These incidents limited the time for repetition of experiments.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter summaries the overall findings and provides some recommendations for further research.

5.2 Conclusions

The present study investigated the interaction between P and salinity in relation to the growth of pasture plants. The examination included 3 components: the effects of salt on soil P, physically and chemically; the effects of salt on pasture plants (biotic factor); and the combined interactions between soil P and salt and pasture plants.

The results of salt impacts on P adsorption confirmed first that there was a significant difference in P adsorption values by soils, depending on their physical and chemical properties. Increasing clay content (surface area) and increasing content of oxyhydroxides dramatically increased the P adsorption.

The effect of introducing salt into the system was investigated by 3 different methods of applying NaCl salt. All methods showed that adding salt increased P adsorption relative to no salt conditions. The present study also suggests that that added salt increased P maximum adsorption (compared to the control, $p < 0.05$). A short incubation procedure produced no significant change in P adsorption with increasing salt concentrations. There were differences in P adsorption in adding salt solution relative to no salt conditions. However, there was no correlation observed in salt solution concentrations and P adsorption. A third procedure, where the prior

contact time between salt and soil was varied showed that contact time affected the adsorption capacity. Shaking soils with NaCl solution in longer period resulted in reduced P adsorption capacity in soils. This was possibly due to some flocculation of clay and reduction in soil surface area.

The effect of salt on the growth of pasture plants was examined in a number of ways. Salt was shown to affect seed germination and plant development. Salinity delayed germination in all species and decreased the germination rate. At the highest salinity used (12 dS/m), no germination occurred. The salt tolerance varied between the plants studied in the order of ryegrass>birdsfoot trefoil> orchard grass= red clover> white clover.

Pot experiments using acid washed sand and half-strength of Hoaglands nutrient solution (minus P) as culture media showed that P additions at concentration of 25-50 ppm were the optimum P level for plants in non-saline conditions. In control experiments where no P was applied, plants exhibited stunted growth. Mineral content analysis also revealed that the highest P content in plant tissue was found with P at 25 ppm.

A ryegrass study at optimum P level (25 ppm) under varying salinity conditions (0-12 dS/m) in sand culture, showed that even though ryegrass has a high ability to tolerate salt, yields were still reduced with increasing salinity level even under optimal P conditions. High Na and Cl contents were observed at high salinity levels possibly leading to toxicity. Salinity therefore is the main retarding factor to growth. Ryegrass plants at different stages of growth showed different responses to salinity - the growth was more severely affected by salinity in the early stages compared to the later stages of growth. The P content in ryegrass plant tissue showed a decreasing trend as salinity increased. Salinity has been reported to inhibit P absorption by

plants leading to decreased P tissue contents (Gauch and Eaton (1942); Fine and Carson (1954); Greenway (1962a); Moukhtar et al. (1974); and Manchanda et al. (1982)).

A sand pot culture involving 2 salinity levels (control and 4 dS/m) under various P levels (3, 10, 17, 25 and 35 ppm) showed that plants grown at high NaCl had significantly less dry matter than those in control treatments. Yields were reduced in all studied species. However, individual species responded differently to salt-P effect with respect to plants' individual ability to uptake nutrients, tolerate salt toxicity and overcome the effect of nutritional imbalance. Plants responded to P positively with increased P additions in non-saline conditions. The most suitable phosphorus level for saline culture varied depending on species. Increasing P up to certain levels increased plant yields under saline conditions. Red clover required a higher P addition to achieve maximum yield in saline conditions (compared to non-saline), while orchard grass and ryegrass gave maximum yield at the same P level in both saline and non-saline conditions. Birdsfoot trefoil data were difficult to interpret because of high variation in yields. Further increases in P above plant requirements either decreased or showed insignificant change in plant yields. Therefore, over the studied range of P, plants responded positively, negatively or showed insignificant change to added P. Mineral contents in plants were very variable and differed between plant species. When P was not constant, P contents in plant tissue tended to increase as salinity increased as well as Na, Cl and Ca contents. The effects of salinity on the contents of other elements in plant tissue were different between plants and varied with growth conditions.

A pot experiment using a natural saline soil was conducted without additional salt, but P was added up to the maximum P adsorption of the soil. The results

suggested no mass response of plants on P additions. Best growth of red clover was obtained at the highest P addition level, but there was insignificant difference to other levels. With the ryegrass plants, the first level of addition P produced the best growth, but with insignificant differences to other P levels. This study indicated that P did not assist in overcoming the effect of salinity in this natural saline soil. Salt reduced yields regardless of P concentration. The lack of response to P application was primarily associated with high salinity, and the associated poor soil structure. The interactive effects between salinity and P fertilisation is therefore likely to be varied with level of fertility, degree of salinity, individual salt tolerant ability of plant and growth conditions. The current study showed that additional P applications had little or no effect on plant yields at relatively high salinity as salinity was considered as the main growth limiting factor more than P nutrition.

This research clarifies, at least in some extent, contradictory from previous studies in the literature on salinity-fertility relationship that plants responded to fertility in saline conditions positively, negatively and no effect of fertility. The outcomes of this study indicate that the interaction between salinity and phosphorus fertility in pasture production systems was complicated and depended on plant species. In variable environments of P and salinity, pasture plants responded both positively and negatively to added P. However, the response of plants to P in saline conditions was similar to non-saline conditions. Plants responded to added P only where salinity was not excessively high and at adequate levels of P. Salinity impacts, therefore, can be reduced by fertilisation at certain levels of P and salinity. The effect of salinity on phosphorus adsorption by soils showed that salt increased P adsorption but was not related to salt concentrations. The management of salt-affected soil and

the improvement of pasture yields under saline conditions are discussed in **Section 5.4**.

5.3 Recommendations for Future Research

The interaction between salinity and P in soils/plants is particularly complex. This current study examined P isotherms in saline conditions and also observed plants grown under various P concentrations in saline environments. However, some investigations could not be completed due to resource limitations and time inadequacy. Some recommendations for future research are provided below.

For P isotherm study, other factors besides those examined in the current study can influence the P adsorption in soils in the presence of salt. These include the initial P saturation percentage, contact time, composition of added salt, and temperature. Some of these have been reported in the literature (e.g., Rajan and Fox, 1972; Barrow and Shaw, 1979), however, additional work is required.

For pot experimental studies, it is recommended that:

- Plants should be studied for different lengths of time of salinity exposure to observe plant development and metabolism under the influences of salinity and fertility;
- The experiments should be conducted under controlled temperature and humidity conditions to eliminate seasonal effects on the pot experiments as the humidity and temperature can affect the salt tolerance capacity of plants. Plants can tolerate salt better in a cool climate than when grown under hot conditions;

- Various degrees of salinity, such as, low, medium and high levels should be included to compare the effects of salt on plants at different degrees in natural saline soil;
- Pot experiments should include investigation of impact of soil physical properties on growth, including root distribution;
- Plant growth periods should be extended to obtain larger yields. In several current experiments, insufficient plant materials were obtained for some plants causing ambiguous results. This will also provide sufficient biomass to allow better analysis of salinity/fertilisation impacts on plant mineral composition. Alternatively, larger pots with greater numbers of plants should be used.

There is a limited amount of information regarding the effects of salinity on growth and concentrations of inorganic elements in plants, as related to soil fertility. The actual response of plants to salinity varies with growing conditions, e.g., climate, water management, agronomic management, and crop variety (Feigin, 1985). To study these variables:

- Plants should be grown in the same season, or time compensation allowed for different growing seasons;
- A study on inward and outward ion movements of plants, subjected to salt concentrations and P additions should be included;
- Nutrient concentrations should be maintained if possible at the constant levels.

A problem with nutrient-salinity research is the difficulty in extrapolating results from the greenhouse to the field. In solution culture experiments, it may be difficult to maintain high concentrations of P over the duration of the experiment because P may precipitate or complex with other ions. Levels of P used in greenhouse research (sand solution cultures) may be an order of magnitude greater than those in the field. Direct toxicity of specific ions to plants from experiments using nutrient solution or sand culture media seems to occur notoriously. In field experiments, soil P availability is dependent on such factors as soil type, (e.g., the fixation and buffering capacity, organic matter content, pH), soil moisture level, climatic conditions and the presence of microbial activity (Rogers et al., 2003). High available P is unlikely to exist in soils (Feigin, 1985).

Most pot experiments have been carried out at constant salt concentrations while the salt concentration of the soil solution in the field may fluctuate or vary greatly over horizontal or vertical distance, with time, as well as with moisture conditions. Migration of salts due to seasonal precipitation, irrigation and crop cycles occurs in the field. Therefore, under field conditions, there is no uniformity in depth and time. The results obtained from uniform experimental conditions cannot be used for accurate prediction in such situations. Bernstein et al. (1974) noted that water and sand culture possess the advantage of greater control over the composition of the medium, but soil culture and field plots may better indicate the range of effects to be expected under normal growing conditions. It is recommended that future research should embrace field experiments with similar experimental factors to compare the results of field and greenhouse studies. The root distribution is likely to be an important factor in experiments, therefore further studies should include investigations of root distribution patterns in field experiments as well.

Additionally, the study reported here indicates some directions for future studies of the interaction effects of several growth factors (e.g., salinity and P) upon yield. This research, combined with existing information will provide a good basis for future studies of productive agriculture under saline conditions. Intensive research is needed to clarify the interaction between the above variables, especially fertility and salinity, to bring about an improvement of saline soil management.

5.4 Saline Soil Management Regime

The establishment of pastures on saline land can improve site productivity, provide ground cover to prevent erosion and return organic matter to the soils. Soil structure would be continually improved by positive interactions between physical-chemical properties. Restoration of hydrologic balance in the ecosystem and finally reclamation could be achieved by plant growth response and improved soil organism activities in those areas (Atwell et al., 1999). In salinised areas, attempts are made to reclaim them by means of leaching, drainage and consequently, revegetation. Establishment of perennial plants on these lands has the advantage of reducing annual maintenance costs and their deeper-rooted habit will assist with water management (lowering the watertable) and reducing recharge, which is a crucial part of salinity control. Nevertheless, in some cases where lands are extremely salt-affected, economic or topographical factors may make this reclamation impossible. Thus reducing the opportunities for soil salinity to occur should be a top priority in land management.

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APPENDICES

APPENDIX 1

Information of Measurement of Salinity and Salinity Units

EC and EC_{1:5}

Salinity in soils can be estimated by the measurement of electrical conductivity (EC) of a soil solution. Many salts dissociate to ionic forms in water (pure water has a very low conductance), so the electrical conductivity of a solution presents a total concentration of salts (Department of Natural Resources Queensland, 1997). Three measures of electrical conductivity are:

EC_{1:5} is the electrical conductivity of a 1:5 soil water suspension, which is one part air-dried soil to five parts distilled water. When the electrical conductivity of the 1:5 soil:water mix is calculated, the result is multiplied by a factor based on the texture of the soil sample. This indicates the soil's ability to hold salt or allow it to be flushed through. The factor varies between 7.5 and 25 (see **Figure A1**), with the result of the multiplication known as the EC_{se} (Taylor, 1991).

EC_{se} is the electrical conductivity of the soil saturation extract, used to predict plant response to soil salinity for a wide range of soil textures. EC_{se} is more meaningful than EC_{1:5} because it is closer to water content and can be related to the large amount of published data on plant salt tolerance (Taylor, 1991; Department of Natural Resources Queensland, 1997; Peverill et al., 1999).

Please see print copy for Figure A1.

Figure A1. Multiplication factors for converting $EC_{1:5}$ to EC_{se} (Taylor, 1991).

EC_s is the electrical conductivity of soil at measured or predicted maximum field water content (approximating field capacity), used to assess salt movement to soil (usually predicted from 1:5 and soil properties). EC_s represents the salt content at the point where soil profile drainage has essentially ceased (Queensland Department of Natural Resources, 1997).

Units used to measure salinity (Queensland Department of Natural Resources, 1997; Rengasamy and Bourne, 1997).

Australian scientists have used dS/m (deciSiemens per metre) as a unit of measurement of electrical conductivity and, hence, salinity. However, there is a number of different units in recording salinity for various reasons, for example, parts per million (ppm) or milligrams per litre (mg/L) in a solution or the measurement of soluble salts in a soil as a percentage of weight of dry soil. There is a range of conversions between different units of electrical conductivity as follow. The unit mol/L (mols of salts per litre of solution) has been excluded, however, due to the lack of use and the complications related to molar masses and involved formulae. **Figure A2** depicts the common units and their conversions.

Please see print copy for Figure A2.

Figure A2. Common EC measurement conversions (Taylor, 1991).

Common Measurement Correlations to DeciSiemens per Metre (dS/m)

- **dS/m = mmho/cm = mS/cm**

(decisiemens per metre = millimho per centrimetre and millisiemens per centrimetre
– all of which are equivalent measurements)

- **dS/m x 100 = mS/m**

(decisiemens per metre by 100 = millisiemens per metre)

- **dS/m x 1000 = μ S/cm**

(decisiemens per metre by 1000 = microSiemens per centrimetre; μ S/cm is a widely used measure)

- **$\text{dS/m} \times 640 = \text{ppm} = \text{mg/L} = \mu\text{g/ml}^1$**

(deciSiemens per metre by 640 = parts per million and milligrams per litre and micrograms per millilitre. These measure total dissolved salts/solids)

- **$\text{dS/m} \times -0.36 = \text{OP}$ in bars (OP = osmotic potential)**

- **$\text{dS/m} \times 10.96 = \text{meq/L of NaCl}$**

(milliequivalents per litre of sodium chloride-varies with type of salt)

- **$\text{dS/m} \times 0.34 = \% \text{ total soluble salts (TSS) in 1:5 mix}$**

(% TSS in an EC 1:5 mix at 25 °C)

Other conversions

- **$\text{mhos/cm} = 1000 \times \text{mmhos/cm (dS/m)}$**

(mhos per centrimetre = 1000 millimhos per centrimetre or dS/m)

- **$\text{mmhos/cm} = 1000 \times \mu\text{mhos/cm}$**

(millimhos per centrimetre = 1000 microhos per centrimetre)

- **$\mu\text{mhos/cm} = \mu\text{S/cm}$**

(microhos per centrimetre = microsiemens per centrimetre)

NOTE: ¹ = To convert from an EC in dS/m to ppm, the factor varies from 530 to 900 depending on the type and its concentration. 640 is used as an accepted average.

APPENDIX 2

Detaileds of Hoaglands nutrient solution and P solutions used

Appendix 2.1 Nutrient Solution Preparation

(Hoagland and Arnon, 1950 and applied from Blair and Wilson, 1990).

The basal nutrient solution (complete solution) was applied to all treatments. The following salts were used;

“A” Solution

(1). $5[\text{Ca}(\text{NO}_3)_2]\text{NH}_4\text{NO}_3 \cdot 10\text{H}_2\text{O}$ use 20.41 g of NH_4NO_3 and 304.04 g of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$.

(2). Fe EDTA (Etylene Diamine Tetraacetic Acid) by adding EDTA = 10.1 g and Fe as $\text{Fe}(\text{SO}_4)_2 \cdot \text{H}_2\text{O}$ = 10.04 g

add (1) and (2) together and made up to 1 L of distilled water to make A solution

“B” Solution

(1). KNO_3 152.02 g

(2). $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 126.65 g

(3). $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ 0.286 g

(4). $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ 0.195 g

(5). $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ 0.021 g

(6). H_3BO_3 0.725 g

(7). $\text{MoO}_3 \cdot 2\text{H}_2\text{O}$ 0.005 g

(8). MoO_3 -anhydrous 0.004 g

(9). KCl 3.154 g

(10). NH_4Cl 27.285 g

add (1) to (10) together and made up to 1 L of distilled water to make B solution and KOH is used to adjust final pH of the nutrient solution to pH 6.0.

Adding 10 mL of A solution and 10 mL of B solution in 5 L of distilled water to make the half strength of Hoaglands solution.

Appendix 2.2 P application; add P as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ Solution

2.2.1 Optimum P for pot experiment at high range of P

Pot contained 500 g of sand was added P at different concentrations of 0, 25, 50, 100, 200 and 800 ppm as $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$

The molecular weight of $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ is 156 which has $31 \text{ gP/L} = 31 \text{ mgP/mL}$

Using 25 mgP/kg sand therefore, 500 g sand there will be 12.5 mg P.

31 mg P using 1 mL of the solution $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ in a pot contained 500 g of sand

12.5 mg P will use = $12.5/31 = 0.4 \text{ mL/pot}$

78 g of $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ made up to 500 mL with deionised water in volumetric flask gave 1 mol/L

1 mol/L of $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ was diluted to 0.1 mol/L by taking 50 mL of 1 mol/L solution made up to 500 ml with deionised water in volumetric flask. **Table A1** presents the volumes of P solution added in each treatment at high range of P concentrations.

Table A1. P levels at high range of P concentrations.

P concen tration (ppm)	Vol. of P soln. (mL) from original concentration	Vol. Nutrient soln. (mL)
0	0	50
25	4 (0.1mol/L)	50
50	8 (0.1mol/L)	50
100	16(0.1mol/L)	50
200	3.2 (1 mol/L)	50
800	2.8 (1 mol/L)	50

2.2.2 Optimum P for pot experiment at low range of P

Each pot contained 500 grams of sand which was added variable amounts of $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ depending on each treatment (0, 0.01, 0.1, 0.5, 1.0, 5.0 and 25 ppm).

The 500 grams of sand used in the experiment had 125 mL of water holding capacity.

The molecular weight of $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ is 156

31g P in 156 g $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$

1 "-----" $156/31 = 5.03$ g of $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$

Therefore weigh 5.03 g $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O} = 1\text{g P} = 1000 \text{ mgP/L} = 1000 \text{ ppm}$

The 7 concentrations of P in the experiments; 0, 0.01, 0.1, 0.5, 1.0, 5.0 and 25 ppm. were prepared by diluting 1000 ppm $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ to 1, 10 and 100 ppm to

obtain different concentrations. The amounts of water, P solutions added to pots for each treatment is presented in **Table A2**.

Table A2. Low ranges of P solution prepared by using $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$.

P Concen. tration (ppm)	Vol. of P soln (mL) from original concentration	Vol. of water (mL)	Vol. Nutrient soln. (mL)
0	0	75	50
0.01	1.25 (1ppm)	73.75	50
0.1	12.5 (1ppm)	62.5	50
0.5	6.25 (10ppm)	68.75	50
1.0	12.5 (10 ppm)	62.5	50
5.0	6.25 (100 ppm)	68.75	50
25	3.125 (1000ppm)	71.875	50

2.2.3 P preparation at the concentrations of 3, 10, 17, 25 and 35 ppm as

$\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$

At the beginning of the experiment, only water and nutrient solution were applied at sand water capacity for each pot. 75 mL of water and 50 mL of nutrient solution were applied to the pots after 2 weeks of the conducting, P and NaCl were added as the following. Water was added to compensate the volume of water capacity of each pot on the day of imposing P and salt solutions after deduction of those solutions. The volumes of NaCl salt solution and P solutions for non- salt and salt treatments are shown in **Tables A3** and **A4** respectively.

Table A3. Volumes of P and salt solutions for the control treatment (no salt added).

P concentration (ppm)	Vol. of P soln. (mL) from original concentration	Vol. of salt solution (mL)
3	3.8 (100 ppm)	0
10	1.3 (1000 ppm)	0
17	2.1 (1000 ppm)	0
25	3.1 (1000 ppm)	0
35	4.4 (1000 ppm)	0

Table A4. Volumes of P and salt solutions for salt treatments (4 dS/m).

P concentration (ppm)	Vol. of P soln (mL) from original concentration	Vol. of salt solution (mL)
3	3.8 (100 ppm)	3.5
10	1.3 (1000 ppm)	3.5
17	2.1 (1000 ppm)	3.5
25	3.1 (1000 ppm)	3.5
35	4.4 (1000 ppm)	3.5

2.2.4 P application for natural saline soil (DP2)

Soil used at 350 g with the maximum P adsorption value at 0.31 mg P/ g soil (P maximum adsorption capacity, PMC).

P was added at 7 levels as KH_2PO_4 with the ranges of 0 P (control), 0.1 x PMC, 0.25 x PMC, 0.35 x PMC, 0.5 x PMC, and 0.7 x PMC and at PMC.

The KH_2PO_4 with the ranges was prepared by diluting 25.8 g and made up to 1000 mL with deionised water. This gave 5.88 mgP in 1 mL. Volumes of P solution added at different levels obtained from the different ratios of P maximum adsorption are shown in **Table A5**.

Table A5. Volumes of P solution as KH_2PO_4 in natural saline soil (DP2).

P Concentration (ppm)	P maximum in 350 g (mg)	Vol. P added as KH_2PO_4 (mL)
0 P (control) =0	0	0
0.1xPmax= 0.031	10.85	1.90
0.25xPmax =0.075	27.125	4.60
0.35xPmax=0.1085	37.975	6.50
0.5xPmax=0.155	54.25	9.20
0.7xPmax=0.217	75.95	12.9
1.0xPmax=0.31	108.5	18.5

APPENDIX 3

Notes in the Soils Used in Laboratory and Pot Experiments

Natural Saline Soils DP1 and DP2

DP1 and DP2 soils were collected in the same area but in different years. DP1 soil sample was collected at 0-20 cm, while DP2 was collected at the depth between 0 and 10 cm. The soil profiles were morphologically similar, but, slight differences were found in soil chemical properties (see **Table A7**).

Site and Profile Description

Location: Duck Pond north of the new dairy in Menangle, NSW, Australia. Duck Pond is located to North/West of Elizabeth Macarthur Agricultural Institute (EMAI), near Navigation Creek. The location (refer to **Figure A3**) was in an abandoned channel at Navigation Creek.

Classification: Fluventic Haplobrept, clayey, mixed, thermic (J. Morrison, pers. comm., 2002.)

Site History: Site located at the low spot, therefore it appears to be a 'sink for salts'. After floods and erosion events, water and soil particles accumulate in this area. Salt crusts can be seen on the surface during drought periods. Nearby dams, creeks and the river also become salty at the bottom. During summer, seasonal cracking is observed.

Physiography: Lower part of broad flat valley in rolling country surrounded by low hills on the S, E, and W.

Topography: Site on a valley floor or valley bottom called "back swamp of the valley"; site about 1 km from the Nepean River. Surface was flat with little microtopography.

Drainage: Site poorly drained, and profile moderately poorly drained

Vegetation: Site covered with grasses, many weeds, patch of mosses, algal growth, succulent plants, with few trees such as Swamp Oaks, Ironbark on hillsides.

Parent material: Alluvium, old lagoon sediments and marine bedrock at depth.

Landuse: Pasture for cattle.

Profile description: There are 3 layers

A₀ (recent flood deposit) 0-10 cm dark grey brown (10YR3/2, moist); silty clay loam; structureless; slightly sticky; rusty mottles; soft and wet; moist 3; porous; many bundles of grass roots; no stones; distinct boundary,

A₁ 10-20 cm moist, dark grey (10YR2/1, moist); waterlogged medium clay with silt; structureless; sticky; water seeps along the cracks; indistinct straight boundary,

B 20-60 cm

B₁ 20-40 cm moist 2; dark grey (10YR2/1, moist); slightly aggregated clay (sign of salinity) becoming strongly aggregated at depth; granular structure; slightly sticky; slight plastic; firm to friable; some roots penetrated through; gradual change,

B₂ 40-60 cm dry (dark yellowish grey (10YR4/4, dry); drier with depth and impermeable; dense earthy clay; poor structure; no stones; no organisms.

N.B. In surrounding landscape, not at the profile site, there was a perched watertable due to impermeable layers found below the surface. Duplex soils and salt accumulated in subsoil were characterised. Surface depleted in nutrients. Impermeable between layers of topsoil and subsoil. Topsoils had lower clay content than subsoils.

Please see print copy for Figure A3

Figure A3. Map of DP1 and DP2 (NSW Department of Agriculture, 2000).

JBU1**Site and Profile Description**

Location: Jamberoo Landscape, upper Saddleback Road, Southwest of Kiama, near summit. Road cutting on SE side road (refer to **Figure A4**).

Classification: Humic Kandiodox, krasnozem clayey, oxidic, thermic (Hazelton, 1992).

Physiography: Site is located near the top of a NE facing slope, about 200 m above sea level.

Topography: Site in rolling country with some steep mid slope positions. Site was on an 8° slope with surface micro topography due to cattle tramping.

Drainage: Site and profile well drained.

Vegetation: Site currently is pasture, historically would have been covered in rainforest.

Parent material: Saddleback Lattite Member-black porphyritic mafic latite.

Climate: Average annual rainfall approximately 1200 mm, with relatively uniform distribution, but summers slightly wetter than winters. Average daily summer temperature is about 21°C, and average daily winter temperature is 14°C.

Profile description: There are 2 layers

A 0-25 cm dark reddish brown (5YR3/4) clay loam; moderately developed fine subangular blocky and granular structure; common fine and medium roots; few stones; few ants and earthworms; indistinct boundary,

B 25-110⁺ cm yellowish red (5YR4/6) slightly stony to sandy clay; massive, breaking to moderately developed subangular blocky structure; common fine and medium roots less than above, very few roots below 80 cm; few strongly weathered stones >70 cm.

TG1

Site and Profile Description

Classification: Grey Kurosol (Isabell, 1996); Aeris Epiaqualt, sandy over clayey, mixed, thermic (Soil Survey Staff, 1975).

Location: Adjacent to the sewage treatment plant at Ulladulla, NSW, Australia. Map reference 6083000mN and 169500mE from the Milton topographic map sheet (8927-2-N) (refer to **Figure A4**).

Physiography: The site is located midway on a gently sloping hill ($<5^\circ$), the slope is to the southeast. The altitude is approximately 20 m a.m.s.l.

Topography: The hills in the area are gently sloping, merging with the coastal plain.

Drainage: The site drains to the southeast into Racecourse Creek. There is an apparent increase in surface water at the lower (eastern) end of the studied area. The presence of mottles in the soil profile indicated that the site was poorly drained. There was evidence that water had seeped out of the wet horizons into the pit, suggesting that water was perched in and above the B horizon and had not penetrated into the lower horizons (P. Walker, pers. comm., 1997).

Vegetation: The site has been cleared of vegetation. The native vegetation was heathland scrub, merging with a Eucalyptus forest (open forest).

Parent material: The area consists of undifferentiated sediments of Tertiary age, close to the boundary of the Permian aged Conjola Formation. The Tertiary sediments comprise sand, gravel, clay, quartzite, sandstone and conglomerate.

Climate: The Ulladulla region has a temperate marine climate. Rainfall averages 926 mm/year, distribution is relatively even with spring tending to be the driest time of the year (CMPS&F, 1994). The summer (January) maximum average daily temperature is 24.3 °C and a minimum average daily temperature of 18 °C, the

winter (July) average daily maximum is 17.1 °C with an average minimum temperature of 7.2 °C (Sinclair, Knight& Partners, 1993).

Profile description: There are 7 layers (after Green, 1997)

A1 0-15 cm moderately moist; dark brown (7.5YR4/2); loamy sand/sandy loam texture with a fine sand fraction; weak pedality, peds 5-10 mm in size; subangular blocky structure; soil fabric is sandy; significant root matter; gradual transition,

A2 15-30 cm moderately moist; brown (10YR4/3), loamy sand/sandy loam texture with a fine sand fraction; weak peds 10-20 mm in size; subangular blocky structure; weak consistency; there are two co-dominant mottles, yellowish brown (10YR5/8) and light grey (10YR7/2); the mottles have a faint contrast that improves with depth, 2-10% abundant; with a gradual transition to the A3 layer,

A3 30-53 cm moderately moist; brown (10YR5/3); sandy loam texture with a fine sand fraction; moderately developed peds 10-20 mm in size; subangular blocky structure with a very weak consistency; there are two mottles, a dominant yellow (10YR7/8) and a sub dominant pinkish grey (7.5YR7/2); there is a faint contrast with 2-10% abundant; the transition is sharp,

Iron nodule layer 53-63 cm matrix had a dark yellowish brown moist colour (10YR4/4); sandy clay with a fine sand fraction; the iron nodules were abundant (50-90%), distribution was stratified with a reorientated orientation and there was no evidence of weathering; the nodules were subrounded and subangular tabular in shape; the bottom of the layer was continuous plates of iron compounds, which were smooth on the bottom and rough on the top; the fragments ranged from gravel (6-20 mm) to coarse gravel (20-60 mm); the transition was sharp,

B2 63-82 cm moderately moist; white colour (10Y8/2); fine sand fraction; light medium clay fraction; pedality was moderate, the peds were 20-50 mm with the

moderate to firm consistency; the peds were rough faced with a prismatic structure; there was a distinct mottle, 10-20% abundant with a strong brown colour (7.5YR5/8); when the clay was broken, a gley formed on the outside, indicating that water and roots preferentially follow the structure of the clay; the aggregate slaked; the transition was clear,

B/C 82-120 cm moderately moist; white colour (2.5Y8/2); sandy clay with a fine sand fraction; although a coarser sand than the above layer; moderate pedality, 20-50 mm, prismatic in shape and rough faced; moderate to firm consistency; aggregates slaked; there were two mottles: the dominant was a strong brown colour (7.5YR7/8), the sub dominate had a dark red colour (7.5R3/6). Both mottles were distinct, the dominant mottle having an abundance of 20-50%, the other 2-10%,

Substrate 120-130 cm the substrates had two moist colours of musky red (10R3/4), and light grey (5Y7/1).

Please see print copy for Figure A4

Figure A4. Locations of soil samples for TG1 and JBU1 (after Truong, 1997).

Table A6.Mineralogy of soils used.

Mineral (%)/ Soils	DP1 (0-20 cm)	JBU1 (0-25 cm)	TG1 (0-30 cm)
Quartz	44	30-40	80
Albite	5		
Anastase	<1		
Smectite	32		
Kaolinite	14		<5
Mica/Illite	3		<5
Halloysite		10-20	
Iron oxyhydroxide	1 (Goethite)	30-50	<5

Table A7. Soil properties of DP1, DP2, TG1 and JBU1.

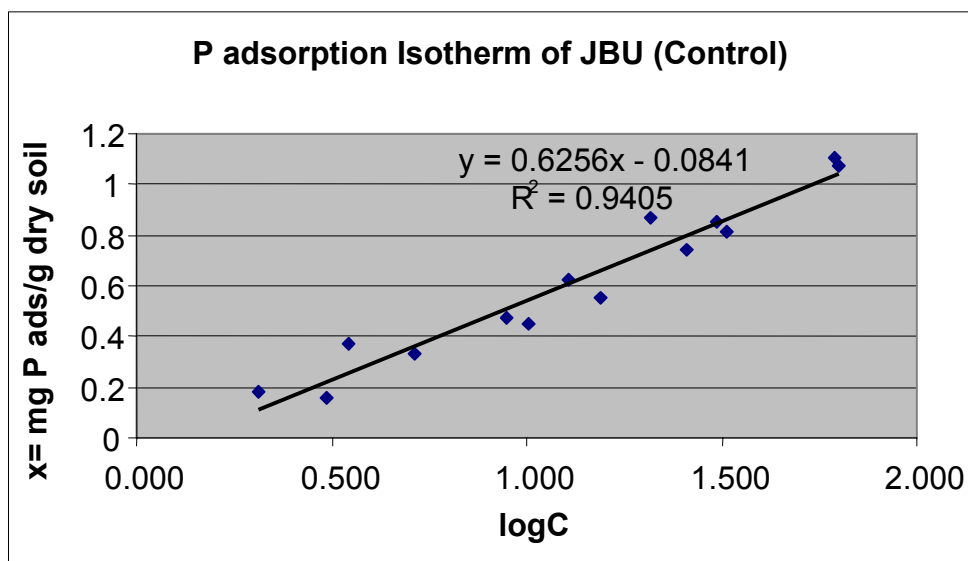
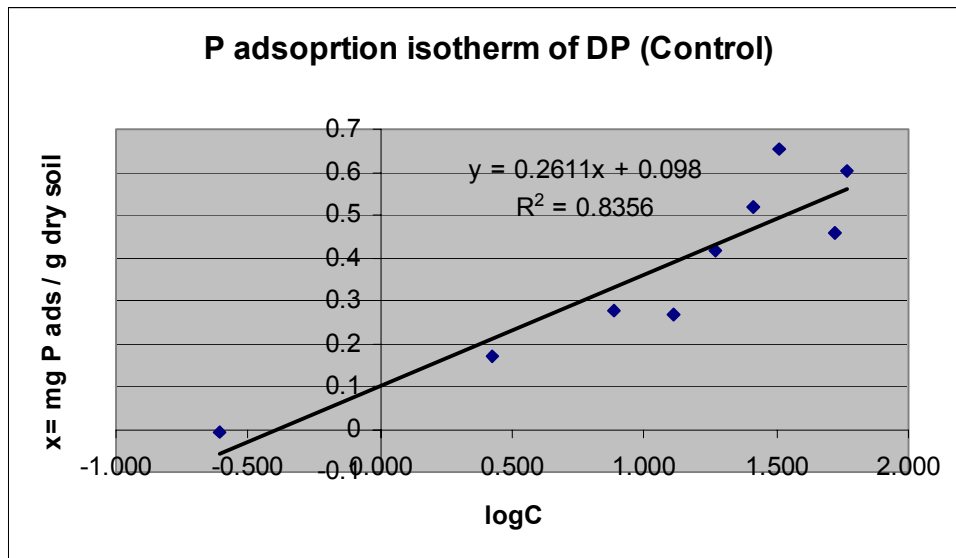
Soil	Depth (cm)	MF	Clay (%)	OC (%)	pH_w	EC	Exchangeable Cations (Cmol/kg)						CEC
							H	Al	Ca	Mg	K	Na	
DP1	0-20	1.06	45	4.14	8.06	3.07	<0.01	<0.01	17	8.7	0.9	0.5	27.1
DP2	0-10	1.08		5.20	8.6	0.85							
JBU1	0-25	1.09	65	5.27	5.17	0.11	0.19	1.36	2.35	2.55	1.26	0.28	7.8
TG1	0-30	1.01	3	1.15	4.6	0.12	0.60	0.59	5.16	1.45	0.97	1.44	10.21

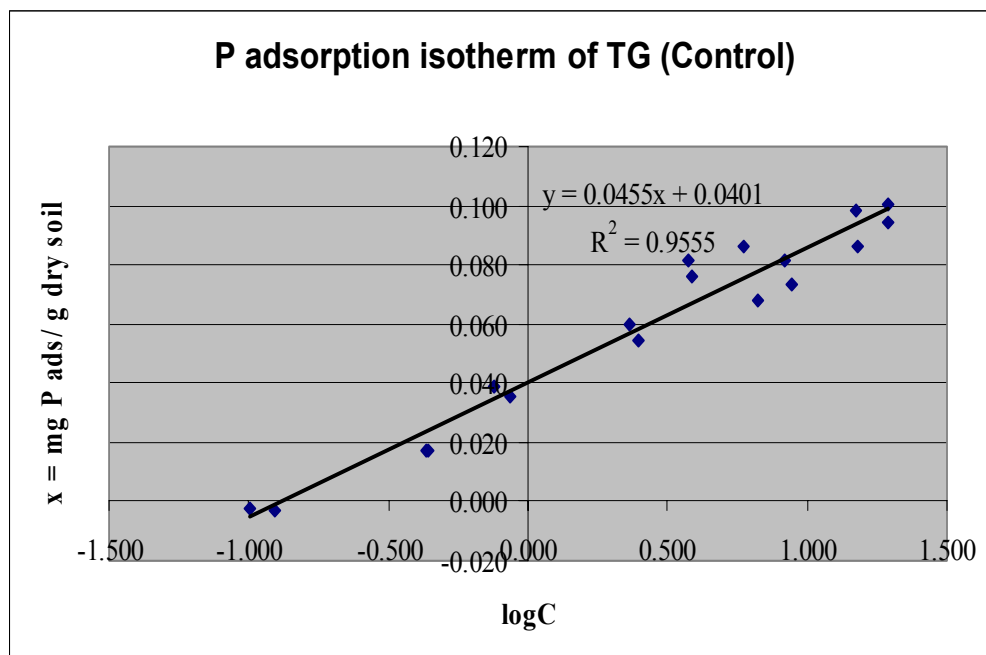
APPENDIX 4

P Adsorption Isotherms for DP1, JBU1 and TG1 soils

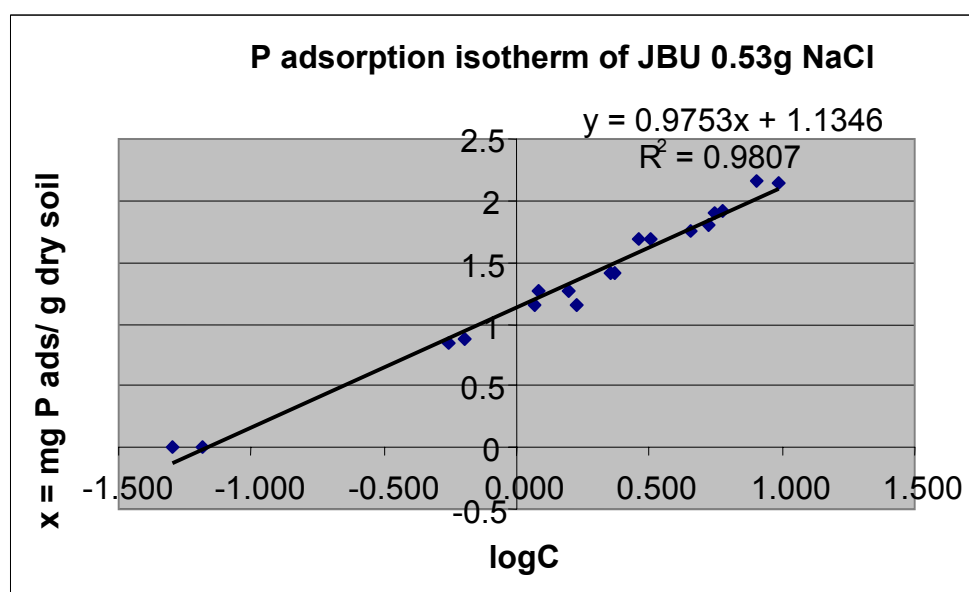
Appendix 4.1 P isotherms of DP1, TG1, and JBU1 soils with no salt addition

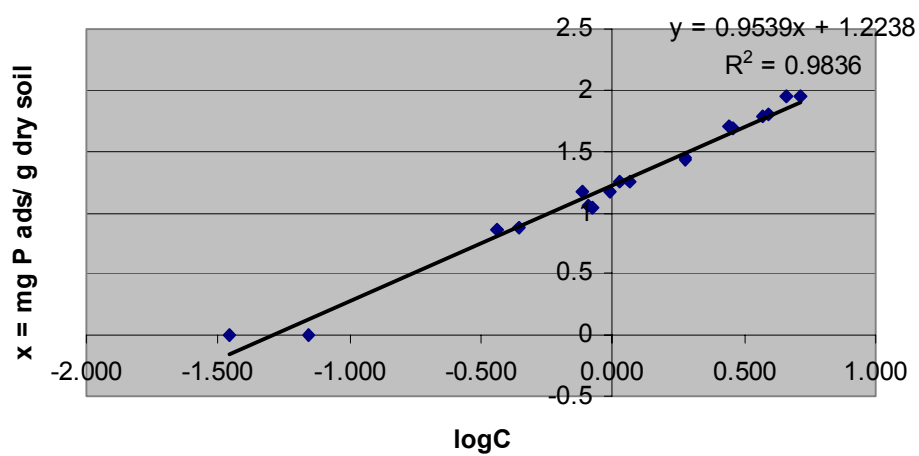
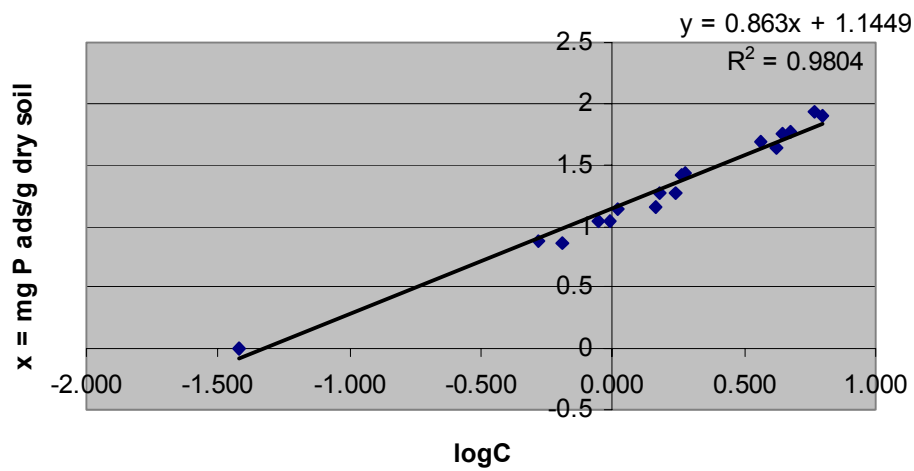
X= amount of P adsorbed in mg / g dry soil, C= equilibrium P concentration (mg/L)

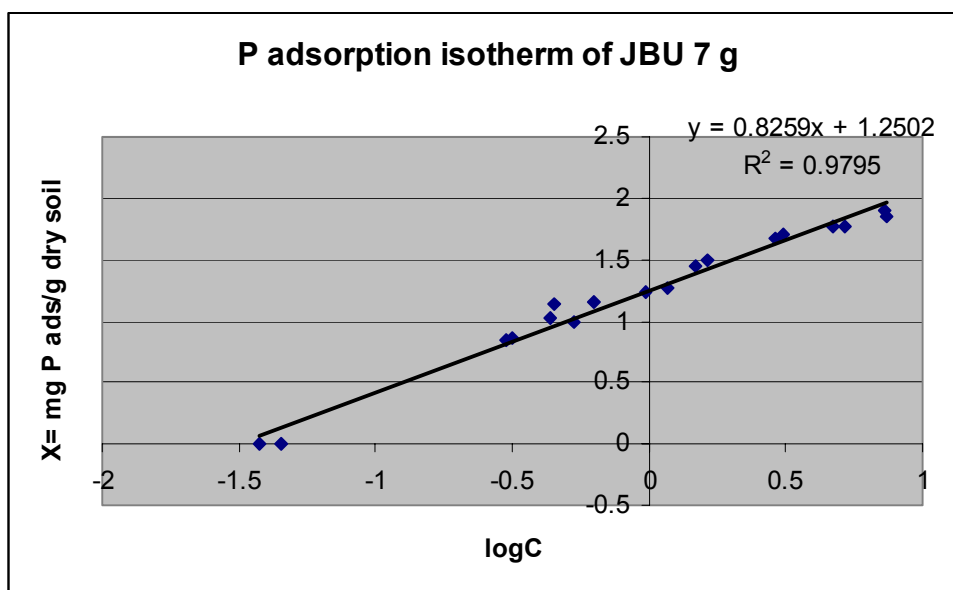
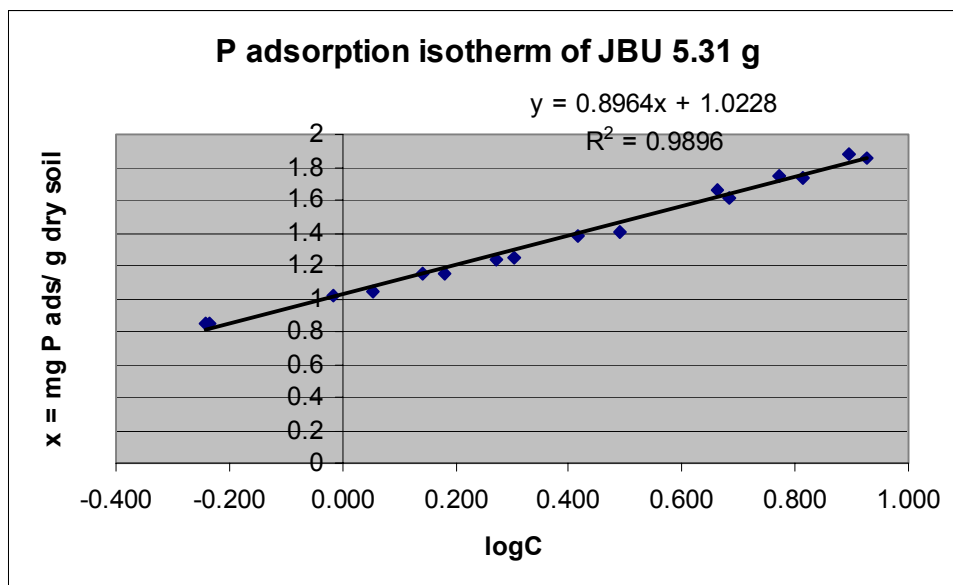


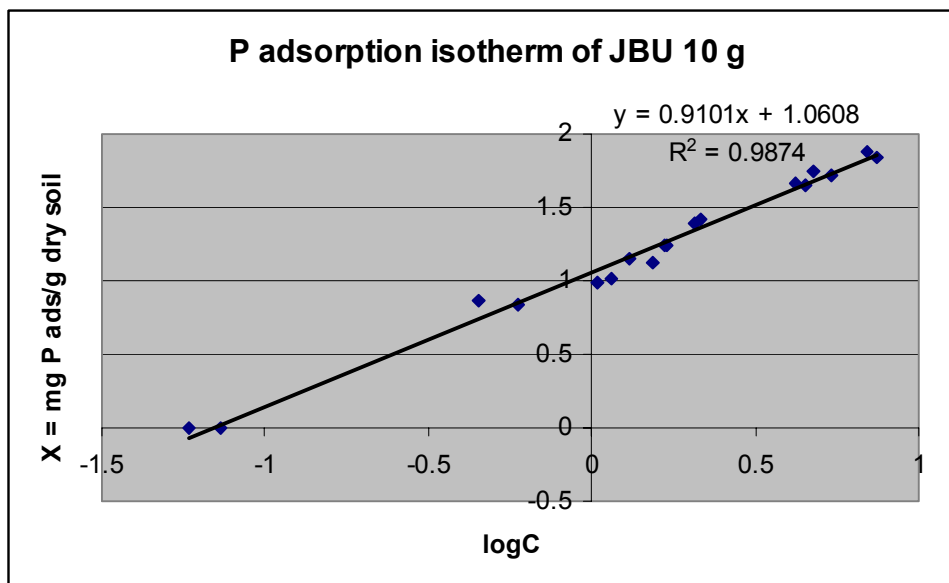


Appendix 4.2. P adsorption isotherms for JBU1 soil after incubation with NaCl salt at various amounts/ 100 g dry soil (0.53 g, 1.22 g, 2.58 g, 5.31 g, 7 g and 10 g).

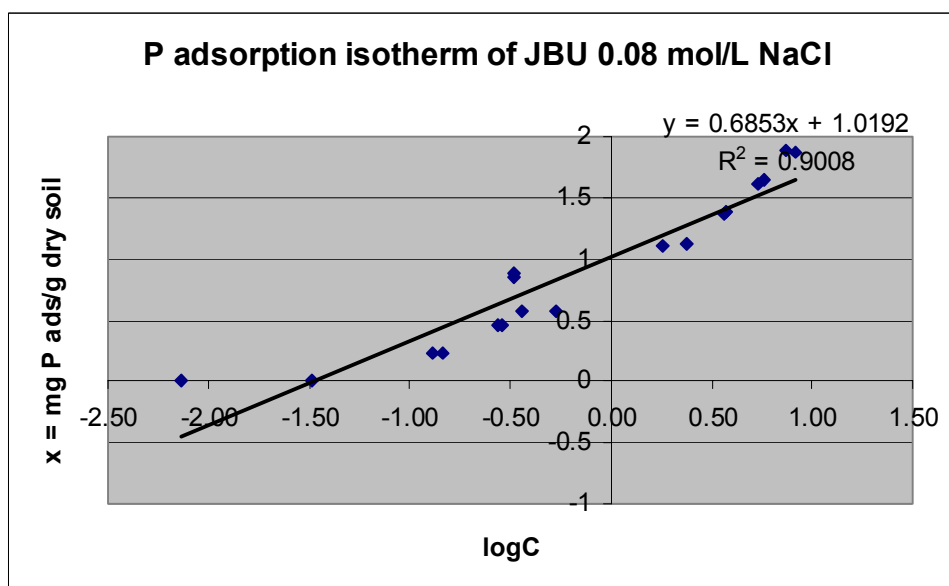


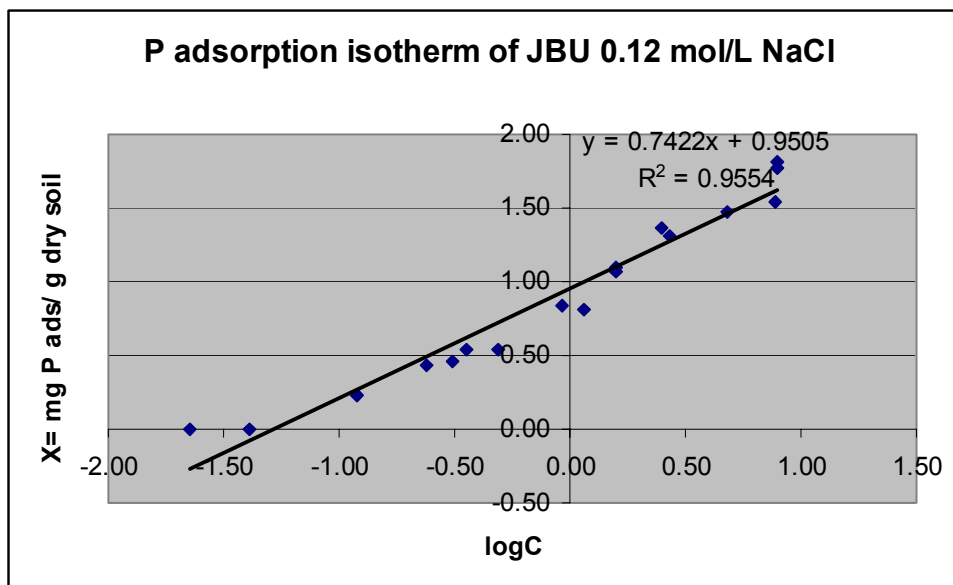
P adsorption isotherm of JBU 1.22 g**P adsorption isotherm for JBU 2.58 g**



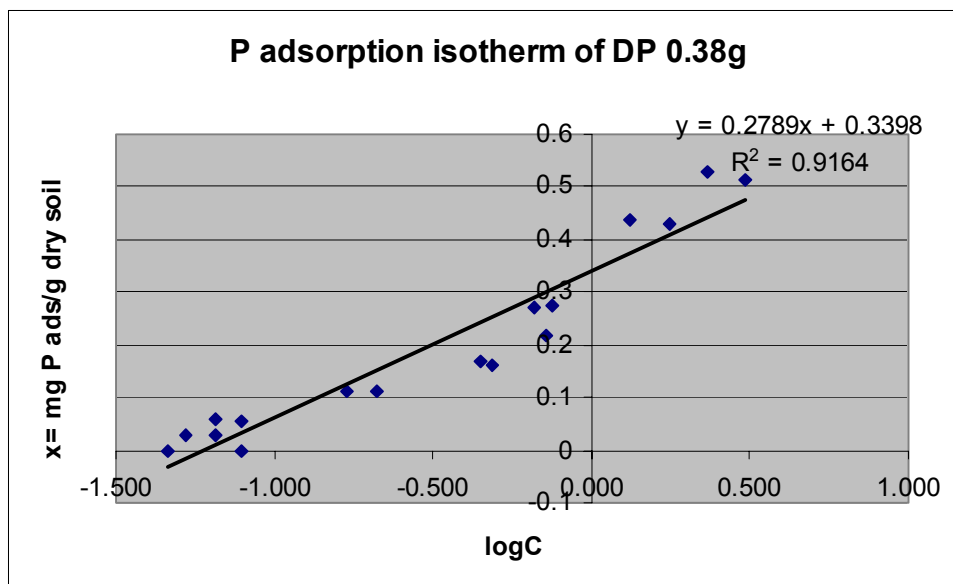


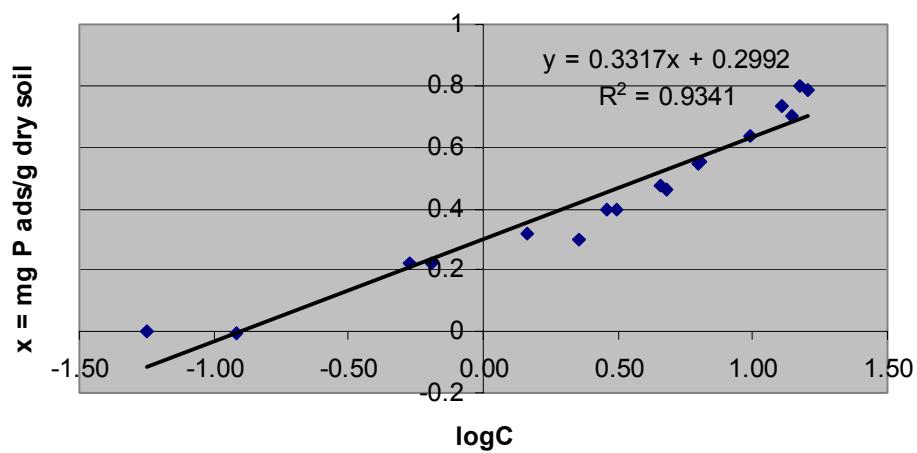
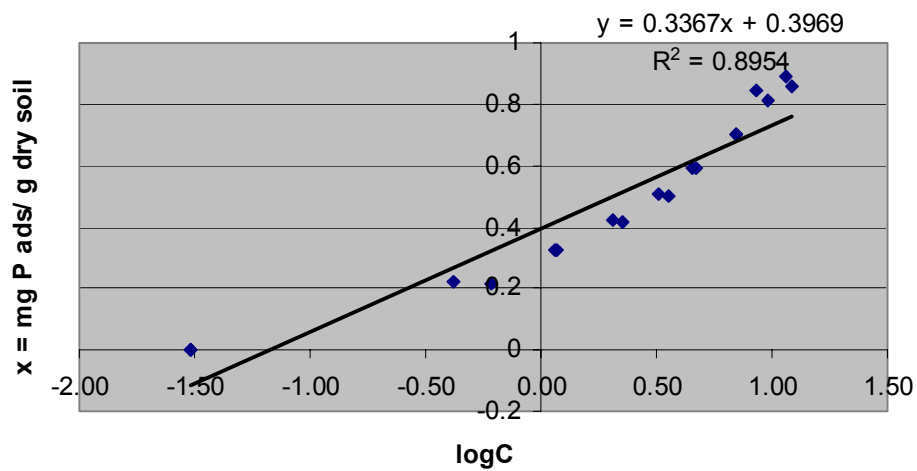
Appendix 4.3 P adsorption isotherms for JBU1 soil with NaCl solution addition to reaction solution at 0.04, 0.08 and 0.12 mol/L NaCl

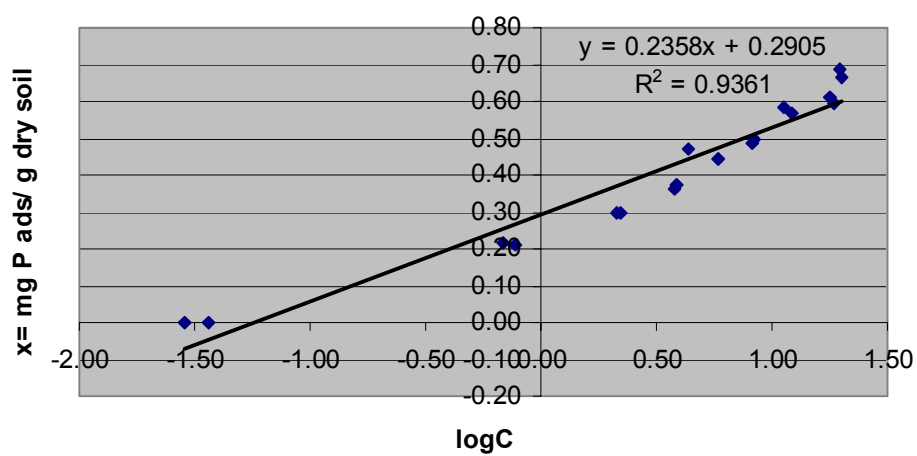
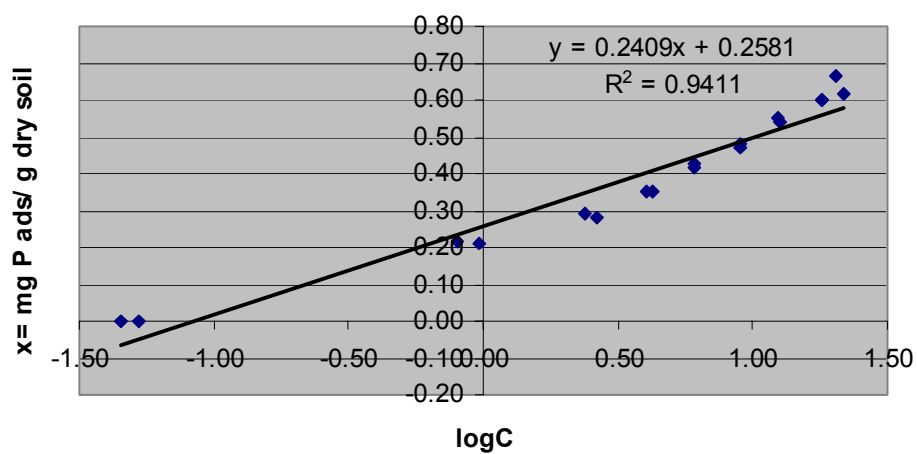




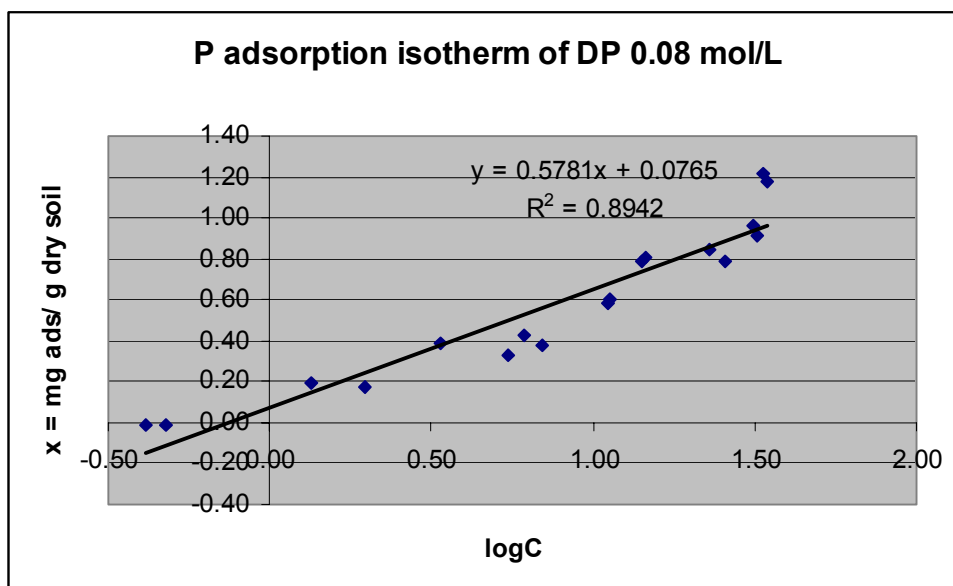
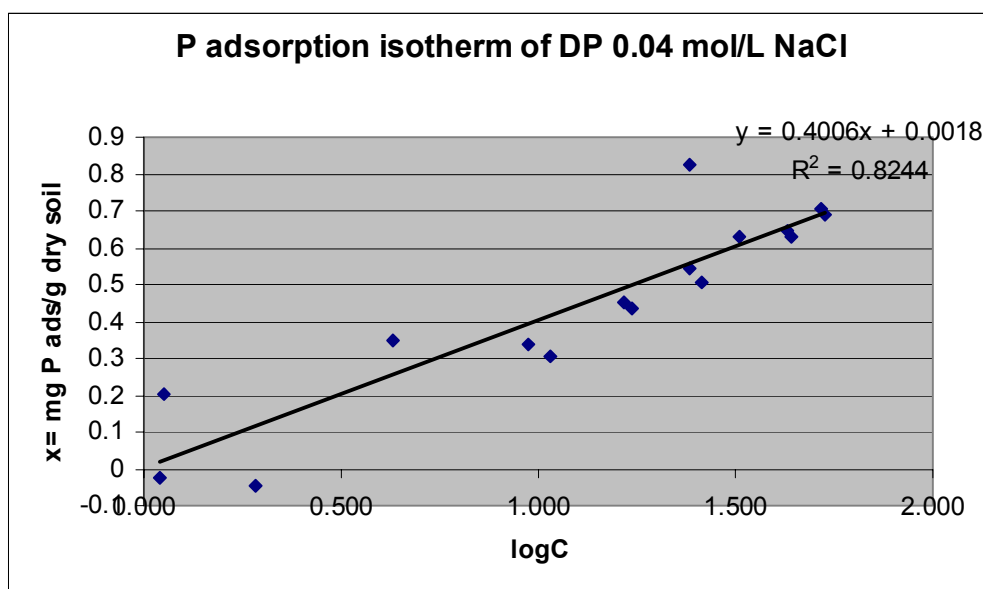
Appendix 4.4. P adsorption isotherms for DP1 soil after incubation with NaCl salt at various amounts/ 100 g dry soil (0.38 g, 1.47 g, 3.64 g, 7g and 10 g).

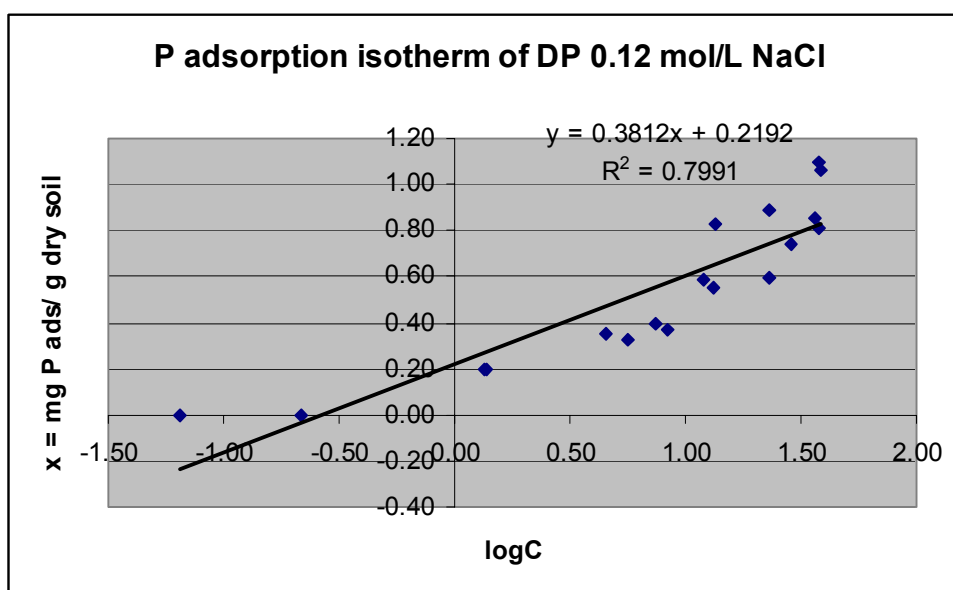


P adsorption isotherm of DP 1.47g**P adsorption isotherm of DP 3.64g**

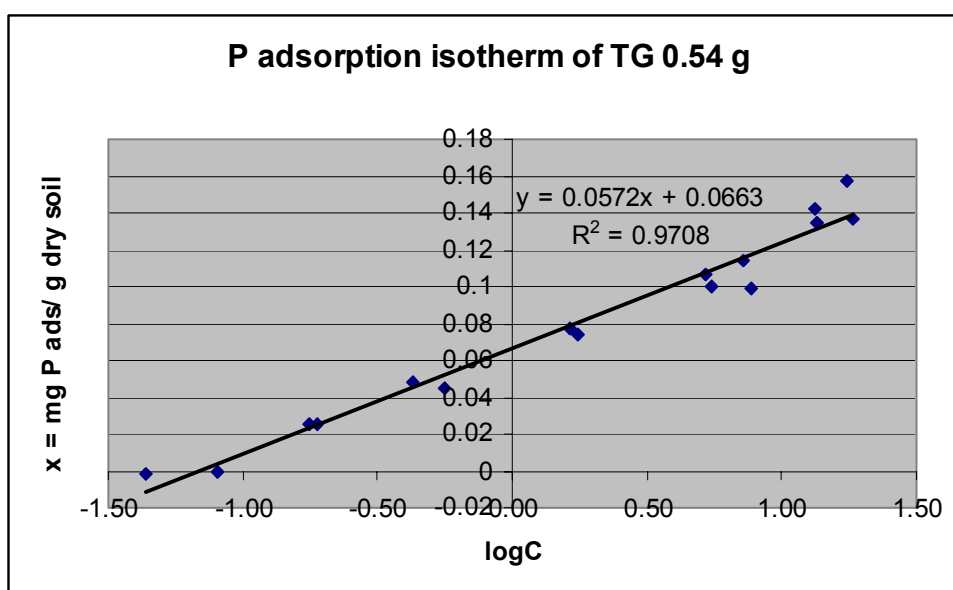
P adsorption isotherm of DP 7 g**P adsorption isotherm of DP 10 g**

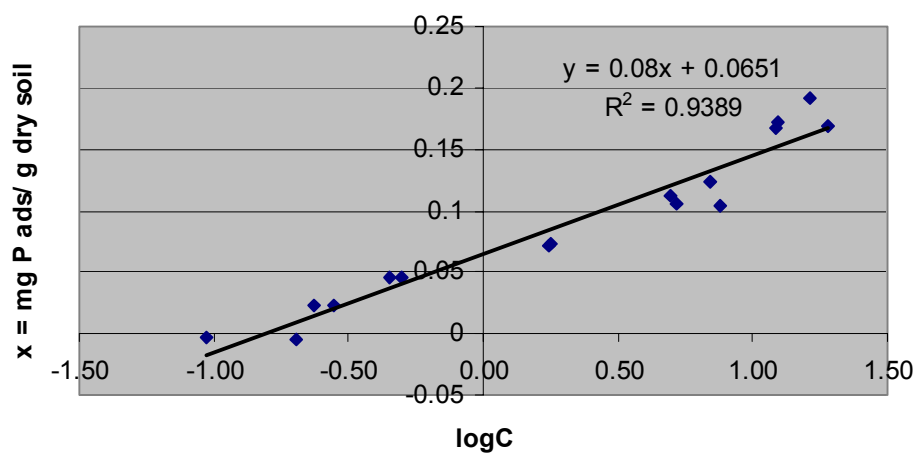
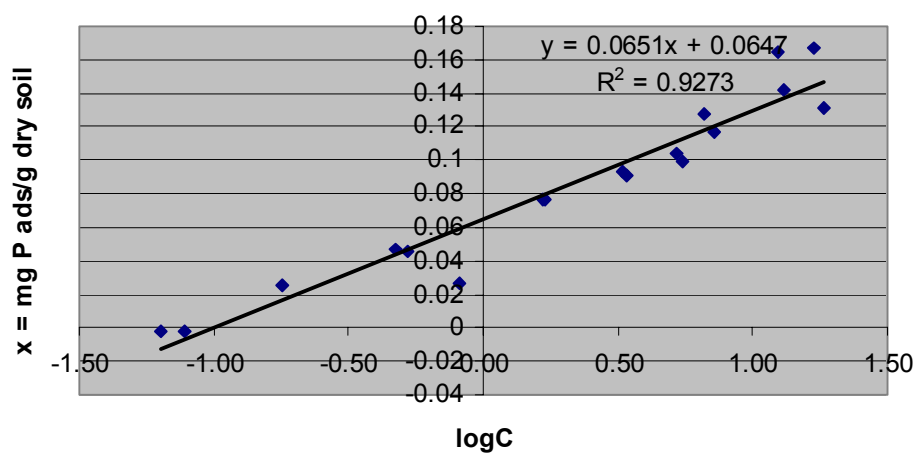
Appendix 4.5 P adsorption isotherms for DP1 soil with NaCl solution addition to reaction solution at 0.04, 0.08 and 0.12 mol/L NaCl

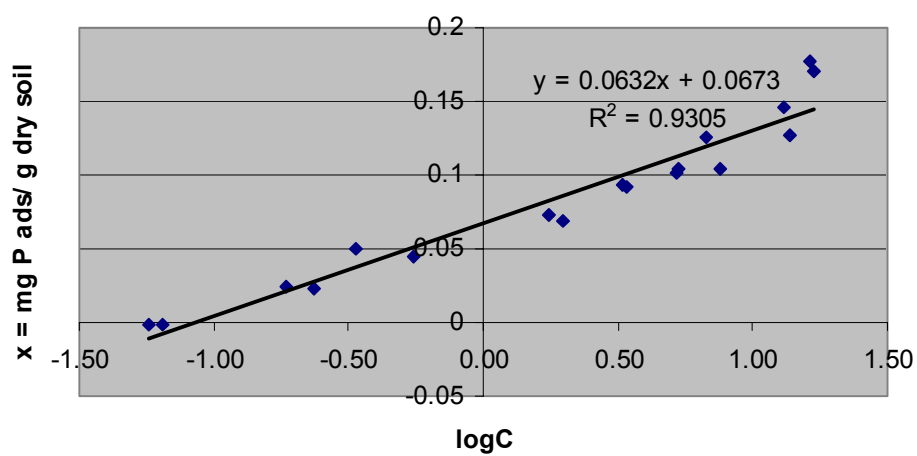
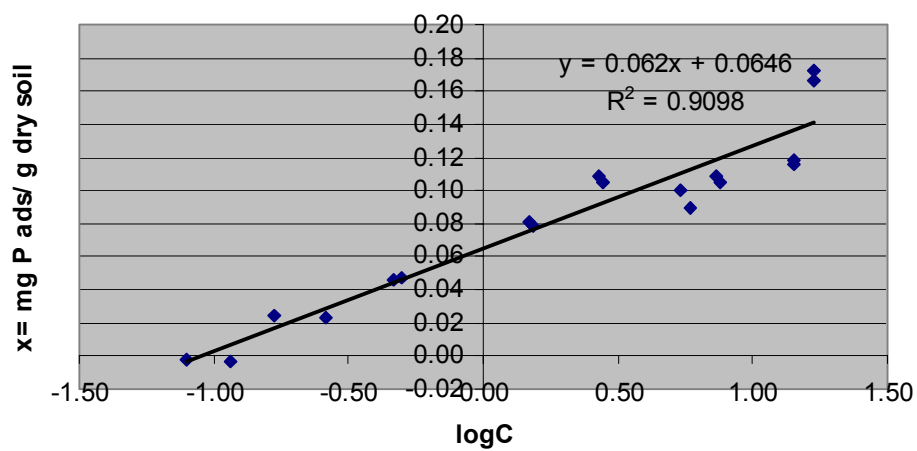


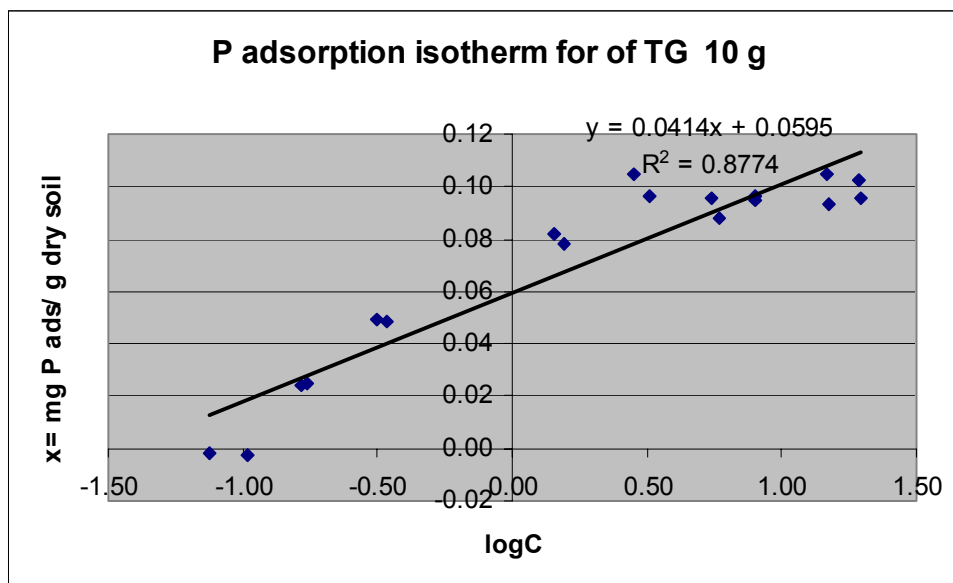


Appendix 4.6. P adsorption isotherms for TG1 soil after incubation with NaCl salt at various amounts/100 g dry soil (0.54 g, 1.22 g, 2.58 g, 5.29 g, 7 g and 10 g).

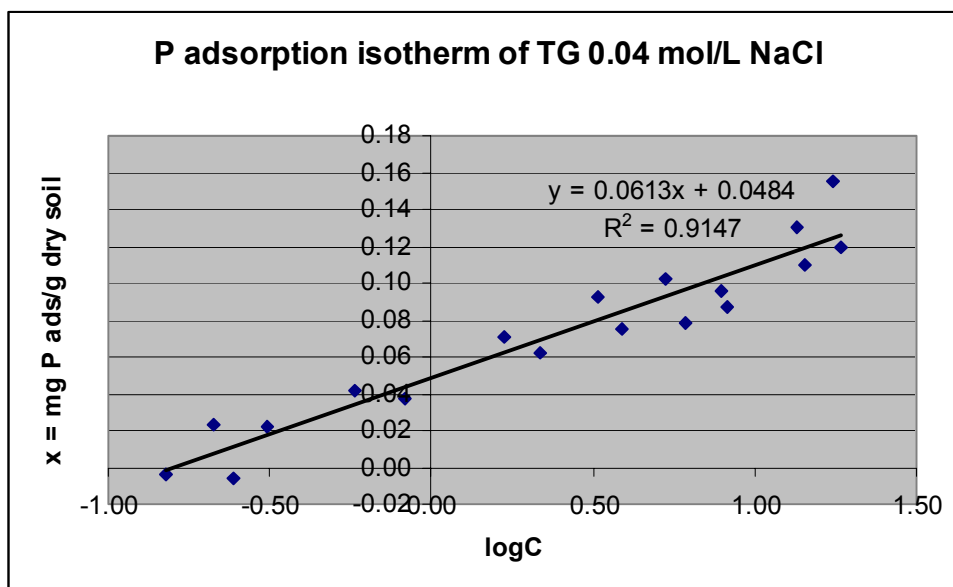


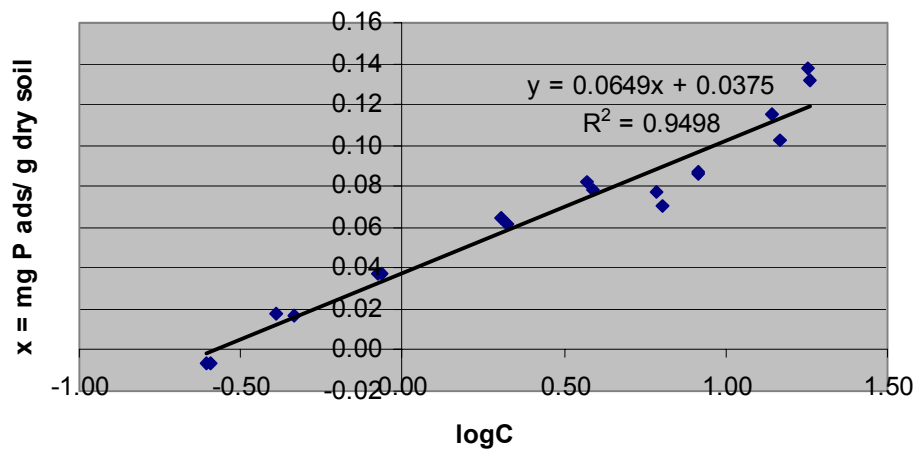
P adsorption isotherm of TG 1.22 g**P adsorption isotherm of TG 2.58 g**

P adsorption isotherm of TG 5.29 g**P adsorption isotherm of TG 7 g**



Appendix 4.7. P adsorption isotherms for TG1 soil with NaCl solution addition to reaction solution at 0.04, 0.08 and 0.12 mol/L NaCl.



P adsorption isotherm of TG 0.08 mol/L NaCl**P adsorption isotherm of TG 0.12 mol/L NaCl**