INVESTIGATIONS ON GROWTH AND P UPTAKE CHARACTERISTICS OF MAIZE AND SWEET CORN AS INFLUENCED BY SOIL P STATUS

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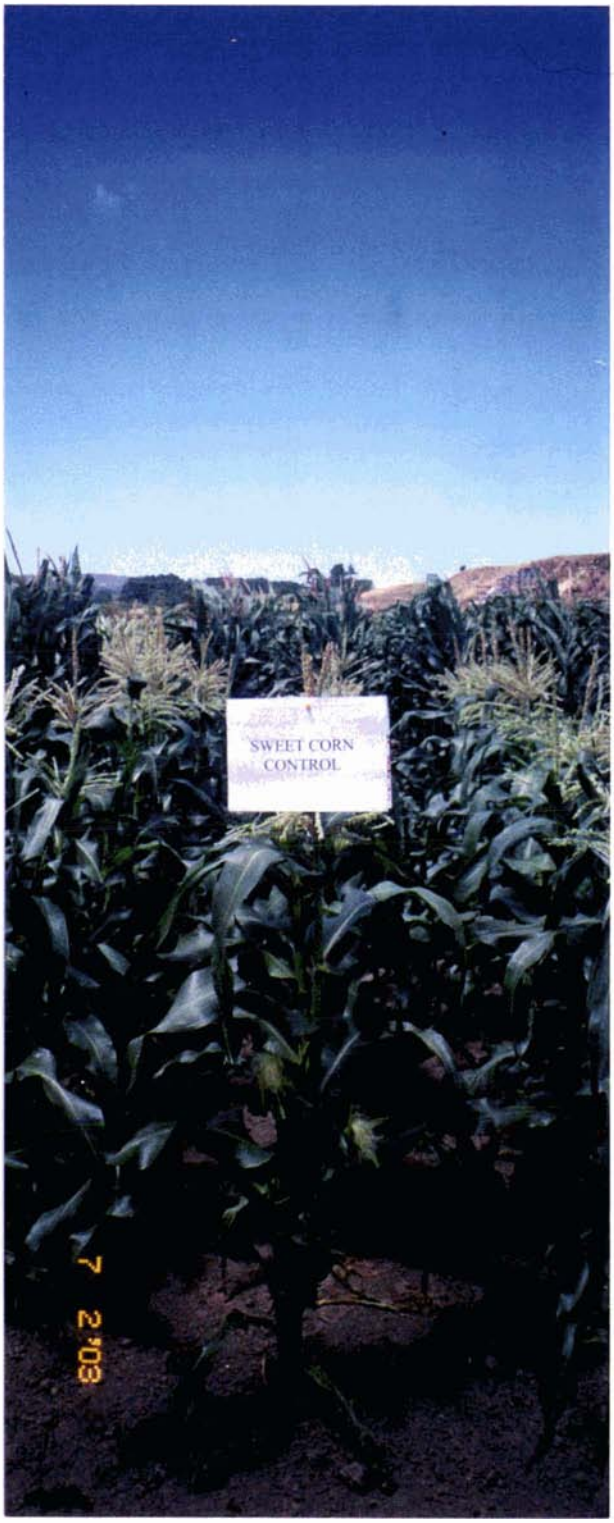
MAIZE
CONTROL
7 2'03


SWEET CORN
CONTROL
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This thesis is dedicated to my family and teachers,

all of them supported a lot and expected from me to fulfil this task one day.

ABSTRACT

Despite being different cultivars of the same plant species (*Zea mays* L.), maize and sweet corn have contrasting P fertiliser recommendations in New Zealand, that are reflected in different target Olsen P values of 10-15 mg P/kg soil for optimum maize growth and 26-35 mg P/kg soil for optimum sweet corn growth. Three key hypotheses were developed in this study to explain why these differences may exist: i) maize and sweet corn differ in their responsiveness to P fertiliser i.e. maize is more internally P efficient and requires less P than sweet corn to grow, ii) both cultivars differ in external P efficiency i.e. their ability to take P up from soil iii) both cultivars differ in external P efficiency because they have different root system structure.

Two field experiments evaluated the growth and yield responses of maize and sweet to different rates of P fertiliser application. The first experiment was conducted in Hawke's Bay (2001-02) and second in the Manawatu (2002-03) with P application rates of 0, 100 and 200 kg P/ha in the Hawke's Bay and 0, 15 and 70 kg P/ha in the Manawatu. Both experiments were conducted on soils of low available P status. The Olsen P test values of 13 mg P/kg soil in the Hawke's Bay and 11 mg P/kg soil in the Manawatu were far below the recommended values for sweet corn (25-35 mg P/kg soil).

In both experiments and across all P treatments maize produced significantly higher dry matter yields than sweet corn during all sampling stages. In the Hawke's Bay experiment at 100 days after sowing (DAS), the maize (87719 plants/ha, 20.9 t/ha) produced 43% more dry matter than sweet corn (71124 plants/ha, 14.6 t/ha), whereas, in the Manawatu experiment (140 DAS), maize (71124 plants/ha, 15.2 t/ha) had a 39% higher dry matter yield than sweet corn (71124 plants/ha, 10.9 t/ha). In both the field experiments, the sweet corn fresh cob yield of 27 and 28 t/ha in the Hawke's Bay and the Manawatu regions and maize grain yields of 16 and 10 t/ha, respectively, were within the range of the reported commercial yields for each region.

In both experiments, the P fertiliser application raised the soil P status (Olsen P test values) but caused no significant increases in either maize or sweet corn yields (total dry matter, sweet corn fresh cob or maize grain). Commercially viable yields of both

cultivars were able to be achieved without P fertiliser application with Olsen P soil test in the range of 10-15 mg P/kg soil.

Sweet corn reached harvestable maturity at 115 DAS in the Hawke's Bay and 140 DAS in the Manawatu experiments. By this time maize had produced 4-6 t/ha more total dry matter yield than sweet corn, yet maize and sweet corn had achieved similar total P uptake (32- 37 kg P/ha at 100 DAS in the Hawke's Bay and 18-19 kg P/ha at 140 DAS in the Manawatu). At silking (after 75 DAS in the Hawke's Bay and approximately 110 DAS in the Manawatu), both cultivar's total leaf P concentrations (0.21-0.25%) were within the sufficiency range values for maize crops in New Zealand (0.18-0.33 %). Maize, however was more internally P efficient growing more dry matter per unit P taken up, which was more noticeable in the drier season. Fertiliser P application increased P uptake with both cultivars under moist conditions in the Hawke's Bay experiment (2001-02). However, the dry conditions in the Manawatu (2002-03) limited P uptake as well as restricted dry matter yields with both cultivars. Further, there were no significant differences between maize and sweet corn P uptake efficiency (kg P/kg root) despite significant differences in the root system structure (biomass) for both cultivars at all stages, which lead to different temporal patterns of P uptake.

The lack of maize yield response to fertiliser P in both field experiments is consistent with the New Zealand recommendations for growing a maize grain crop (because soil Olsen P was in the range of 10-15 mg P/kg). Howevcr, the lack of sweet corn yield response in both field experiments does not support the New Zealand recommendations for growing sweet corn (which assume optimal Olsen P values are 26-35 mg P/kg).

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CHAPTER 1

GENERAL INTRODUCTION

1.1 Maize and its types

Maize (*Zea mays* L.), also known as corn, apparently originated in Mexico where it is thought to have been cultivated by the year 5000 BC (Jugenheimer, 1976; Benson and Pearce, 1987; FAO, 1992). Following European discovery of the Americas, maize cultivation began in Northern America, Europe and moved with European colonists to Africa, Asia, and Australasia (Benson and Pearce, 1987; FAO, 1992). In New Zealand (NZ), maize was successfully grown in the early nineteenth century, and by mid century constituted an integral part of NZ agriculture system (Rhodes and Eagles, 1984).

Botanically, maize belongs to the grass family, Gramineae, and is a tall annual plant with an extensive fibrous root system. Maize is often divided into several different groups or types based on grain characteristics which vary both genotypically and phenotypically. Most types fall into five main categories such as dent maize, flint maize, floury maize, popcorn and sweet corn (Jugenheimer, 1976; FAO, 1992). The last category of maize, sweet corn differs from the other maize types because the sucrose-starch conversion is inhibited, and as a result the kernels remain with high sugar content (Ferguson et al., 1978). Moreover, several mutant genes condition the endosperm making it sweet when consumed about 18-20 days after pollination (Zuber and Darrah, 1987).

Maize is the third largest arable crop in NZ with an estimated area of 30,000 ha. The most widely grown maize types are the dent maize (*Zea mays indentata*) and sweet corn (*Zea mays sacchorata*). Maize is grown for grain mainly in the Waikato, Manawatu, Bay of Plenty, Gisborne and Hawke's Bay areas (Reid et al., 2001a). It is primarily used as poultry and pig feed and as a supplement feed to other animals such as deer, horses and other livestock (Bansal and Eagles, 1985; Chappell, 1985; Hardacre et al., 1991; Sayer, 1991). About 70% of the NZ maize production is used for animal feed, the remaining 30% is milled and used to produce food products such as breakfast cereals,

cakes, breads, biscuits, cooking oils, etc and industrial products such as starch and glue (Chappell, 1985; Hardacre et al., 1991).

Sweet corn has been under growing practices in NZ since the 1960's. It is a vegetable crop grown for both fresh and process markets, with the area under production expanding rapidly in New Zealand. It is reported that the area under sweet corn has almost doubled (from 2989 to 6380 ha) between 1990-2000 (Anon, 2000). Sweet corn produced is mainly used in food industry for local consumption and overseas export. It is also estimated that fresh and processed sweet corn earns approximately 53.5 million dollars annually by export (NZ Horticulture Facts & Figures, 2003). Sweet corn is grown mainly in the Gisborne, Hawke's Bay, Canterbury and Waikato areas (Reid et al., 2001b).

Successful maize and sweet corn production always depends on adequate nutrient and water supply. It is well known that three main nutrients, nitrogen (N), phosphorus (P) and potassium (K), are essential for maize and sweet corn growth and optimum yield. New Zealand research studies have reported contrasting P fertiliser requirements for maize and sweet corn, even though they are cultivars of the same species. Below this we consider the basis for this investigations.

1.2 Fertiliser P recommendations for maize and sweet corn in New Zealand

After reviewing and conducting field experiments in the North Island for growing maize, Steele (1985) recommended a maintenance application of 50 kg/ha of P fertiliser when Olsen P (0-150 mm soil depth) is 11-14 mg P/kg and an additional 20-30 kg P/ha as starter if soil P is less than 11 mg P/kg. Based on recent studies (field experiments) and a review of earlier work, Reid et al. (2001a; and 2002) revised the fertiliser P recommendations for growing maize crop. Their revision was based on field data obtained for maize grown under a very wide range of soil and climatic conditions in New Zealand from 1996 to 1999. Detail of their field experiments are given in Chapter 2, section 2.5.1. Their final recommendations were to apply no P fertiliser when Olsen P > 10 mg P/kg and apply only 20-35 kg P/ha as starter when Olsen P is < 10 mg P/kg (Reid et al., 2001a; and 2002).

In contrast, for growing sweet corn, much higher Olsen P levels have been recommended. For example, Clark et al. (1986) recommended Olsen P soil values of 30 -35 mg P/kg for optimum yields, while Prasad et al. (1988) support estimated target Olsen P values of 28. Currently, the Olsen P test threshold is recognized as 35 mg P/kg, above which P fertiliser addition is unlikely to improve sweet corn yield (Reid et al., 2001b). Furthermore, Reid et al. (2001b) have also suggested that if Olsen P is 26-35 mg P/kg then P fertiliser may increase yield slightly, but such applications are unlikely to be profitable. If Olsen P value is less than 26 mg P/kg, however, then 35 kg/ha of P fertiliser is recommended to be applied as a starter fertiliser (Reid et al., 2001b). The detail of the field experiments on sweet corn (NZ) are given in Chapter 2, section 2.5.2.

If current recommendations for New Zealand are followed, soils used for growing sweet corn have to be raised to an Olsen P status 20 units higher than for maize. In many soils 10-16 kg P/ha (150 mm soil depth) are required to raise Olsen P 1 unit. Therefore, between 200-320 kg P/ha of fertiliser P may be required which will be very expensive. The most expensive nutrient is phosphorus (superphosphate) at approximately $2.10/kg, then N at $1.15/kg and K at $0.79/kg (July 2005 prices-http://www.ravensdown.co.nz). Phosphorus is the main driver of production in New Zealand and therefore, it is essential to adjust soil P status to the economic optimum. In addition, raising the soil P concentrations this much higher could have adverse environmental consequences. Hedley et al. (2002) indicate that Olsen P values > 25 mg P/kg soil on low P sorption soils increase the risk of excessive P loss to drainage and runoff waters. If Olsen P values do not need to be raised to 26-35 mg P/kg soil for sweet corn production, then production costs and environmental pollution could be reduced.

Supporting the above suggestions, there is little research evidence from overseas or New Zealand that sweet corn is more responsive to fertiliser P than maize (Bole and Freyman, 1975; Sanchez et al., 1991). Maize produces higher dry matter yields than sweet corn (see section 3.3.1.5 and 3.3.2.5 in Chapter 3), therefore it might be expected that P fertiliser requirements for maize would be higher than sweet corn. There do not appear to have been any direct comparisons of the P fertiliser requirements of maize and sweet corn. Furthermore, the literature contains no analysis of why sweet corn should have a greater need than maize for P fertiliser to grow.

1.3 Aim of this study

Considering all the above mentioned aspects, the overall aim and objective of this study was "To compare the P fertiliser responses of maize and sweet corn" at vegetative and reproductive stages, and overall yields under different environmental field conditions. To achieve this, hypotheses were developed from a review of the literature. These hypotheses were tested in field experiments in the Hawke's Bay (season 2001-02) and Manawatu (season 2002-03). The next Chapter reviews the relevant literature and the hypotheses are reported in section 2.9.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Under New Zealand maize and sweet corn cropping systems, when supplies of soil water are adequate, the main nutrients affecting crop growth and yield are nitrogen (N), phosphorus (P) and potassium (K). These nutrients are mostly applied as granular chemical fertiliser form. Yield responses to K are rare and likely to occur only on sites where MAF Quickest K values are less than 5, equivalent to 0.35 me K/100g (Reid et al., 2001a; b). In contrast, the effect of N on growth and yield is large and readily quantifiable (Reid et al., 2001a; b). Maize takes up large quantities of N and yield responses have been recorded even in crops that follow pasture (McLaren and Cameron, 1990). The effect of P on growth and yield is substantial but less clearly quantifiable than N (Reid et al., 2001a; b), because maize grows well in soils of low P status.

As mentioned in Chapter 1, maize and sweet corn are cultivars of same species, *Zea mays* L., but in New Zealand have contrasting P fertiliser recommendations to grow despite many of the current agronomic practices for growing sweet corn being based on maize research. The recommended soil P status (Olsen P test value) to grow sweet corn is much higher (almost three times) than maize. The evidence used to develop these P fertiliser recommendations for maize is based on many field experiments conducted in different districts and years. By comparison, the P fertiliser recommendations for sweet corn are based on very limited experimental work.

The literature contains no direct comparison of the P fertiliser requirements of maize and sweet corn, nor any discussion of why the two may differ. In order to consider these questions, this review i) gathers existing information on P fertiliser responses of maize and sweet corn in NZ and overseas, and ii) examines relevant information on the mechanisms that could explain any such differences between the crops. This mechanistic information is classified under the following main areas:

- the amount of nutrient required by the crop for optimum yield;
- the amount of nutrient removed in different plant parts;
- the ability of soil to provide that nutrient;
- the efficiency with which added fertiliser is used by the crop;
- the efficiency of the root system in nutrient uptake.

2.2 Role of P in plant

Phosphorus (P) is the 4th macronutrient other than C, H, O in order of the amount needed by plants and is the second most important nutrient (after nitrogen) in optimising plant growth, crop yields and quality (Bundy et al., 2005). It is an essential element, or nutrient, for the normal life cycle of plants and deficiencies that limit biological productivity in whole ecosystems (Richardson et al., 2005). Briefly, P is essential for all living organisms and responsible for a wide range of plant metabolic functions (Mengel and Kirkby, 1987; Hedley et al., 1995).

The lack of P can have serious effect on plant growth and reproduction. P plays many important functions in plants including involvement in the genetic code, transformation of solar to chemical energy during photosynthesis and provides chemical energy for biosynthesis in plants and membrane formation. It would be difficult to list all individual processes limited by inadequate P supply, however, some of the important physiological processes include cell division (Mengel and Kirkby, 1987), the stimulation of root growth (Barber, 1984; Lynch, 1995) and tillering and grain formation in cereal crops (Mengel and Kirkby, 1987). For more detail see recent reviews (Bundy et al., 2005; Hanlon et al., 2005; Johnston, 2005; Ragothama, 2005).

P is heavily used as a key nutrient for successful growth of crops in New Zealand (Williams, 1998). The concentration of total P in many New Zealand unfertilised soils is low, and much of the P is not readily available for uptake by plants. As a result, in order to sustain productivity, more fertiliser P is applied to New Zealand soils than any other nutrient (McLaren and Cameron, 1990). Processes that govern the availability of soil and fertiliser P to plants are shown in Figure 2.1 (P_o and P_i stands for organic and inorganic phosphorus) and discussed below.

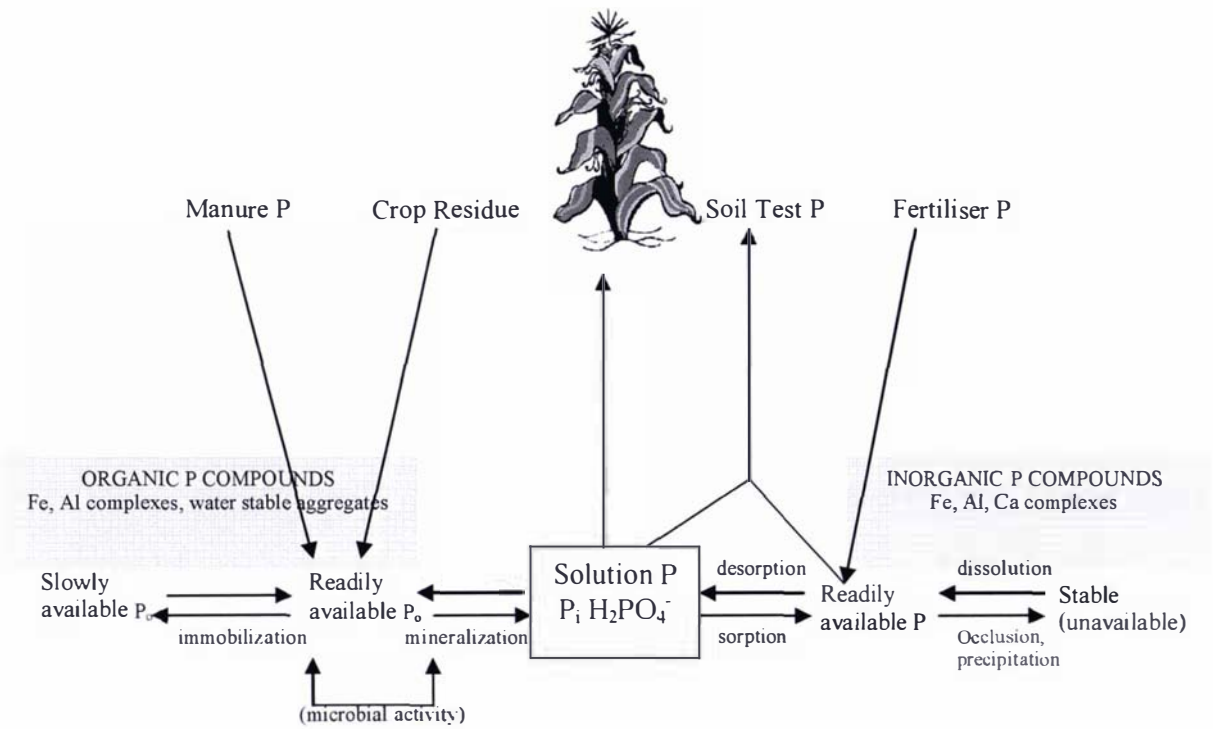


Figure. 2.1 Process that govern the availability of soil and fertiliser P to plants.

2.2.1 Soil P

The total P content of soil 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). P is relatively immobile in soil (Barber, 1984) and plants meet their P requirements from native soil P sources and from added P fertilisers (Figure 2.1). The two forms of P in soil are organic P (P_o) and inorganic P (P_i). There are a range of P_o and P_i compounds and complexes that range in their solubility and availability to plants. In general, P_o forms are solubilised by enzymic hydrolysis (mineralization), whereas P_i availability is governed by dissolution, desorption and exchange reactions (Frossard et al., 1995) (Figure 2.1). The heart of the P dynamics is the soil solution pool. A simplistic view is that P in soils is made up of the three fractions, which are in dynamic equilibrium as shown below (Mengel and Kirkby, 1987; Zoysa, 1997).

Soil solution $\leftrightarrow$ Labile P $\leftrightarrow$ Non-Labile P where,

Labile P = readily available P ($P_i > P_o$) & Non-Labile = slowly available P ($P_i \leq P_o$)

The soil solution P fraction is the phosphate dissolved in soil solution and it is the immediate sources of P for plant uptake by roots. The labile P fraction is the solid phosphate, which is held on soil surfaces and consists of P freshly absorbed onto Fe and Al oxides and the surfaces of other soil minerals. The non labile or stable P fraction is mostly composed of P_o and various mineral P compounds that are rather resistant to dissolution and may release P only very slowly into the labile P pool (Zoysa, 1997). Stable P_o is created from decomposing plant or animal residues forming complexes with Fe and Al hydrous oxides and/or stable aggregates with clay and silt particles (Hedley et al., 1995). Micro-organisms decomposing carbon rich plant residues may also immobilise solution P_i ($H_2PO^-_4$) into newly formed tissue and residues (Stevenson and Cole, 1999).

Phosphorus may enter into soil solution by desorption of P_i associated with the solid phase or by mineralization of P_o. The phosphate concentration in the soil solution itself is very low, and for unfertilised soils is generally below 0.3 μg P/ml (McLaren and Cameron, 1996). Literature also shows that most annual crops require about 0.2 μg P/ml in soil solution for their optimum growth (Fox et al., 1974). However, there is a large variation in the P requirements of plants and the requirement differs with plant species. Depending upon the crop grown, total P removed by the crop varies from 19 to 54 kg/ha (Table 2.1) (Stevenson and Cole, 1999). Briefly, plants need P for their optimum growth and this P must be continually available during the growing season. Thus a significant pool of readily available P is required to maintain adequate levels in the soil's plant available status.

2.3 Methods of assessing nutrient P availability

For crop production system, the basic methods of assessing nutrient P availability in fields are soil testing and plant analysis. For annual crops, adequate P nutrition at the seedling stage is important for plant development because deficiency of P at this stage cannot be remedied by side-dressed P due to the lack of mobility of P in soils (Hedley et al., 1995). For these, pre-plant soil tests commonly taken from the 0-150 mm soil depth are the appropriate method of predicting P requirements for cereal crops (McLaren and Cameron, 1990; Cornforth, 1998). In contrast, plant P analysis is more suited to permanent crops and may be the most suitable method for monitoring the effectiveness

of fertiliser programmes (Westernman, 1990). It is also useful for researchers to identify plant cultivars that are P efficient (e.g. Caradus, 1991; Hedley et al., 1994).

Table 2.1 Approximate amounts of P removed from soil per season by specific crops.

Crops	Yield (t/ha)	P removed (kg/ha)
Grain maize	12.4	52
Grain sorghum	8.1	54
Wheat	5.4	34
Barley	5.4	28
Oats	3.6	22
Rice	7.3	25
Sugarcane	67.2	19
Grasses (general)	8.1	20

Source: Stevenson and Cole, 1999

2.3.1 Soil P testing

Kamprath and Watson (1980) reported three common purposes of soil P tests i) making fertiliser recommendations ii) providing an index of the amount of P a soil can supply and iii) predicting the probability of getting a profitable response to application of fertiliser P. Comprehensive reviews of various soil P tests developed in different countries for assessing the P status of soils have been produced (Kamprath and Watson, 1980; Hedley et al., 1995). The most common methods used to determine plant available P are the alkaline bicarbonate extraction method of Olsen et al. (1954) developed for calcareous soils, and the acid ammonium floride extraction method of Bray and Kurtz (1945) developed for acid soils. In New Zealand, the Olsen P test is now in common use and the results of this test have proved extremely useful for predicting likely responses to phosphate fertilisers for both crops and pasture (McLaren and Cameron, 1996; Cornforth, 1998; Morton et al., 2000). In some instances the Olsen P test is used in combination with the P retention test (an estimate of a soil's capacity to fix phosphate) as means of predicting phosphate fertiliser requirements (Cornforth, 1998; Morton et al., 2000). The P retention of clay soil is medium to high and sandy soil

is low (McLaren and Cameron, 1996). Table 2.2 provides approximate ranges which can be used to assess soil P status for agricultural crops and pastures as well.

Table 2.2 MAF soil P test nutrient ranges in New Zealand.

Nutrient P	Very Low	Low	Medium	High
	----------Olsen P test values (mg P/L)----------			
Rainfall >1000 (mm/year)				
Autumn	0-10	11-20	21-30	>30
Spring	-	-	0-20	>20
Rainfall <1000 (mm/year)				
Autumn	-	-	0-20	>20
Spring	-	-	0-10	>10

Source: Cornfor , 1998

2.3.2 Plant P analysis

Plant analysis provides an effective method for determining the nutrient uptake pattern of crops and confirming nutrient deficiencies, once the relationship between plant part, physiological maturity and nutrient concentration are established (Moller Nielson, 1980). The part and the time most commonly selected for plant analysis of grain crops have been a specified leaf sampled at or near anthesis (a leaf near the ear at silking for maize), or the entire above ground plant as the head is emerging from the boot for small grains (Hanway and Olsen, 1980). Plants contain between 0.1 and 0.4% P on a dry matter basis (McLaren and Cameron, 1990; Hedley, 1998) (Table 2.3) and crop requirements are between 5 and 50 kg P/ha/year, depending on the type of crop and its yield (McLaren and Cameron, 1990).

It is reported that if the percentage of P (expressed on an oven-dry weight basis) for crops exceeds 0.25%, the P concentration of the plant is considered sufficient. But if the P concentration is less than 0.20%, the plant is considered to be low in P, and if less than 0.10%, the plant is considered to be very deficient (Hanway and Olsen, 1980). Very little or no yield increase from P fertiliser application can be expected in maize

when P content of leaf exceeds 0.33% (Arnon, 1975). Table 2.4 provides values of nutrient concentration below which plants are deficient.

Table 2.3 Mineral nutrient concentration ranges in healthy plants expressed as percentage or concentration of dry matter.

Macro-nutrients	Percentage (%)
Nitrogen (N)	2.0-4.0
Phosphorus (P)	0.1-0.4
Potassium (K)	1.0-3.0
Sulfur (S)	0.2-0.5
Calcium (Ca)	0.5-3.0
Magnesium (Mg)	0.1-0.5
Sodium (Na)	0.2-1.5

Source: Hedley, 1998

Table 2.4 Nutrient concentration (dry matter basis) below which plants are deficient ([1]Feeke's growth stage, [2]youngest fully expanded leaf).

Crop	Type of sample	N (%)	P (%)	K (%)
Maize	Earleaf at early silking	2.0	0.15	1.25
Wheat	Whole plant FS3[1]	4.2	0.24[2]	3.0
Barley	Leaves (tillering)	3.9	0.44	3.4
Oats	Leaf blade (tillering)	3.9	0.45	3.4

Source: McLaren and Cameron, 1990

2.4 Maize and sweet corn growth, development and nutrient requirements

2.4.1 Growth and development stages

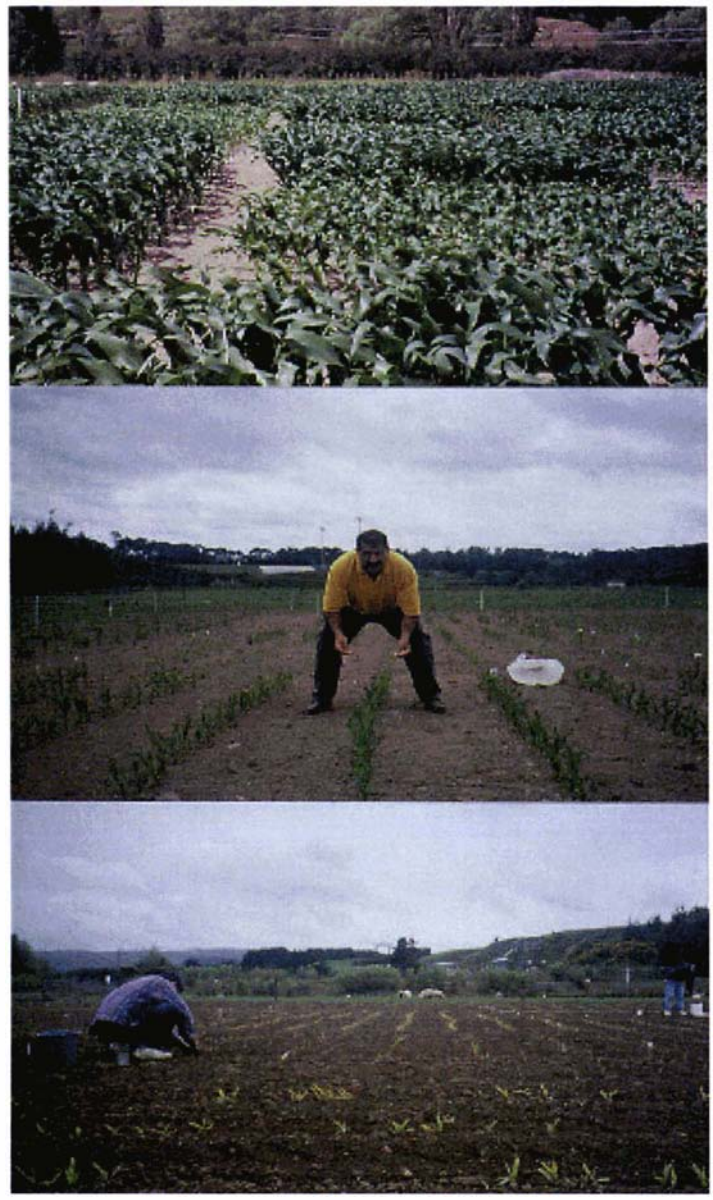
Maize and sweet corn are the same species (*Zea mays* L.); therefore, the growth and development for both cultivars are very similar. Unlike maize, sweet corn is harvested when kernels are immature so that sweetness and pericarp tenderness are optimum for fresh consumption (Wolfe et al., 1997). Therefore, sweet corn has a shorter growing season compared with maize and on this basis might be expected to have different nutrient requirements. This part of the literature review briefly covers the processes involved in and terms used to describe the growth and development of maize (for more detailed accounts see Berger, 1962 and Ritchie, 1997).

Growth and development usually occur together, but are not the same (Reid et al., 2001a; b). Growth is accumulation of mass and is measured in kg/tonnes, whereas development is accumulation of growth stages and is described in terms of leaf number or name of stage (Reid et al., 2001a; b). The maize plant development can be divided into vegetative (V) and reproductive (R) stages. The common name of each stage is listed in Table 2.5 (Ritchie, 1997). A generalised maize plant develops 20-21 leaves, silks about 65 days after emergence, and matures about 125 days after emergence, depending on temperature (Plate 2.1 and 2.2). The first and the last vegetative stages are VE (emergence) and VT (tasselling), where vegetative stages are designated by leaf number V1, V2, V3 ...Vn, where n will vary with hybrid and environmental differences.

Table 2.5 Maize crop vegetative and reproductive stages.

Vegetative stages	Reproductive stages
VE (emergence)	R1 (silking)
V1	R2 (bister)
V2	R3 (milk)
V3	R4 (dough)
Vn (number of leaf)	R5 (dent)
VT (tasselling)	R6 (maturity)

Source: itchie, 1997



(c

(b

(a

Plate 2.1 Sweet corn emergence to vegetative stages in the Manawatu experiment during 2002-03. The crop was planted on 22 October, 2002. VE stage at 25 DAS (a); V1-V5 stage at 40 DAS (b); and V6-V9 stage at 74 DAS (c).

(a) (b)

Plate 2.2 Sweet corn reproductive stages in the Manawatu experiment during 2002-03 season. R1/R2 stage at 100 DAS (a); and R6 stage at 140 DAS (b).

At VE stage under suitable soil and climatic conditions, the planted seed absorbs water and begins growth. The radicle (primary root) is first to develop from the seed followed by another 3 to 4 lateral seminal roots (Plate 2.3). Plant emergence will normally occur within 4-5 days after planting under warm and moist conditions, but under cool or dry conditions the emergence can last up to 2 weeks or longer. After emergence each leaf stage is defined according to the upper most leaf whose leaf collar is visible (V1, V2, V3 ...Vn) (Table 2.5). By V3-V5 stage, the total above ground plant height is about 20 cm with 3 to 5 full visible leaves with little stem (stalk) elongation. At V6-V8 stage, increased stem elongation occurs and new leaves are developed.

By V10 stage, the appearance of new leaf stages will shorten, generally occurring every 2-3 days and the plant begins a rapid steady increase in nutrient and dry matter accumulation which continues until the reproductive stage. At this particular stage (V10), soil nutrients and water supplies are in great demand to meet the needs of this increased growth rate. At the V12 stage, the ear shoots are formed and the number of potential kernels (ovules) on each ear and size of the ear can be determined. The V15 stage is approximately 10-12 days away from the R1 (silking) stage, and is a crucial period of plant development in terms of seed, or grain yield, determination with a new leaf stage occurring every 1-2 days. By V17/V18 stage, the upper ear shoots have grown enough that their tips are visible at the top of the leaf sheaths surrounding them. The tip of the tassel may also be visible at this stage (V17/V18) and the maize plant is now about one week away from silking, and ear development is continuing rapidly. The final vegetative stage (VT) begins approximately 2-3 days before silk emergence, during which time the maize plant will almost attain its full height and pollen shed begins. The pollen shed, also termed pollen drop, usually occurs in the late mornings and early evenings under field conditions.

The R1 stage (silking) begins when any silks are visible outside the husks and 2-3 days are required for all silks on a single ear to be exposed and pollinated. The silks will grow from 2.5-3.8 cm each day and will continue to elongate until fertilised. In this stage (R1), the kernel is almost engulfed in the surrounding cob materials (technically termed the glumes, lemmas and paleas) (Plate 2.2) and is white in colour on the outside. Environmental stress at this time (R1) causes poor pollination and seed set, especially moisture stress, which tends to dessicate the silks and pollen grains resulting in a

'nubbin' (an ear with barren tip). Potassium uptake is essentially completed, and nitrogen and phosphorus uptake are rapid at this stage. Leaf analysis for nutrients (nitrogen and phosphorus) in the plant at this stage is highly correlated with final grain yield and yield response to fertiliser applications (Ritchie, 1997). The R2 stage (blister) begins 10-14 days after silking, in which kernels are white on the outside and resemble a blister in shape. Starch has just begun to accumulate in the watery endosperm and the kernels are in the beginning of rapid steady dry matter accumulation, or the seed fill period. Total nitrogen and phosphorus are still rapidly accumulating and relocation of these nutrients from vegetative to reproductive plant parts has begun. The kernels are now at about 85% moisture content, which will gradually decline until harvest. The R3 stage (milking stage) usually begins at 18-22 days after silking and the kernels display yellow colour with milky white inner fluid due to starch accumulation. The kernels are in their rapid rate of dry matter accumulation and have about 80% moisture content.

The R4 stage (dough) starts at 24-28 days after silking and at this time the starch accumulation has ceased and the milky inner fluid has turned to a thick paste. The embryo continues to develop rapidly through this stage and kernels are now 70% moisture content and have accumulated close to half of their mature dry weight. R5 stage (dent) continues at 35-42 days after silking in which all kernels are dented. The R6 (physiological maturity) stage begins at 55-56 days after silking when all kernels on the ear have attained their maximum dry weight, or maximum dry matter accumulation. The average kernel moisture content at this stage is usually 30-35%, however, this can vary depending upon hybrids and environmental conditions. The grain is not yet ready for harvest and it may be advantageous to let the crop partially dry in the field before harvesting as long as field losses do not become a problem (see section 2.4.3 for nutrient N & P uptake or removal with maize and sweet corn).

Plate 2.1 and 2.2 shows vegetative and reproductive stages of sweet corn hybrid Challenger in the Manawatu field experiment during the season 2002-03 (emergence to physiological maturity stage, crop was planted on 22 October, 2002).

2.4.2 Climatic requirements

Maize is grown over a wide range of climatic conditions but most production is in the latitudes 30^0 and 47^0 north and south of the equator (Benson and Pearce, 1987). Maize grown further north, or south, in temperate climates is mainly used for forage (Benson and Pearce, 1987; Hardacre et al., 1991). Temperature, solar radiation and moisture are ultimately the key environmental factors that determine the growth potential of maize (Shaw, 1977; Major and Hamilton, 1978; Benson and Pearce, 1987; Muchow et al., 1990; Jamieson and Francis, 1991; Wilson et al., 1995; Jamieson et al., 1995; Stone et al., 1999). Temperature affects both growth and development, whereas the main effect of soil water and solar radiation is on growth (Major and Hamilton, 1978).

2.4.2.1 Temperature

Maize is a crop whose growth and development are strongly influenced by temperatures between 10 and 30^0C (Duncan, 1975) with optimal daytime temperatures between 21 and 27^0C (Shaw, 1977). The highest corn yields have been obtained with daytime temperatures of 24-30^0C (Benson and Pearce, 1987). Under New Zealand conditions, studies have demonstrated that temperature is of primary importance in determining the rate of development of maize plants (Eagles and Hardacre, 1979a; b; Muchow et al., 1990; Jamieson et al., 1995; Wilson et al., 1995; Stone et al., 1999). To predict the rate of plant growth and development as influenced by temperature, the use of growing degree days (GDD) is more widely accepted to compare genotypes and predict the crop maturity (for detail see section 3.3.1 Chapter 3).

Soil temperatures of approximately 6 to 8^0C and air temperature of approximately 15^0C are considered to be the minimum for maize growth (Eagles and Hardacre, 1979a; b). Seedling maize plants may withstand temperatures as low as -2^0C for short periods of time (<12 hrs) but long exposure can be fatal (Eagles and Hardacre, 1979b). Since maize requires warm, frost free conditions during the growing season for reliable yields, therefore, in New Zealand this restricts the majority of grain production to the Auckland, Waikato, Bay of Plenty, Poverty, Hawke's Bay and Manawatu regions plus a small area in south Island (Hardacre et al., 1991; Jamieson and Francis, 1991).

Stone et al. (1999) reported that maize grown under warmer soil temperature tends to intercept more radiation and to accumulate more biomass and yield. The authors found that increased soil temperature treatment accelerated the rates of leaf tip appearance and full leaf expansion, enabling the crop to attain more rapidly the total leaf area index. Overall, this generated a 21% difference in maize crop biomass and yields between coolest (18.5^0C) and warmest (25.2^0C) soil temperatures treatments. In their experiment, grain yield increased by ca. 0.3 t/ha per 1^0C increase in average soil temperature across the range 18-25 ^{0}C.

2.4.2.2 Water availability

In New Zealand, soil water received as rainfall represents the most important form of plant available water for maize production. Literature shows that a desirable climate for maize is one in which precipitation is sufficient to wet the soil to field capacity down to rooting depth before sowing, plus rainfall of at least 375 mm during the growing season (Arnon, 1975). Water deficits at anthesis or silking are the most detrimental to yield (Robins and Domingo, 1953; Glover, 1959; Denmead and Shaw, 1960, Berger, 1962). Drought stress during early tassel development causes stunted growth and poor tassel development and during the grain filling period may cause reduction in yield as much as 22% (Robin and Domingo, 1953). On the other hand, excess water (saturated soil conditions) can also reduce yield because wet soils are poorly aerated and cause reduced root activity and nutrient availability (Arnon, 1975; Benson and Pearce, 1987). Therefore, maximum yield is likely to be obtained only if optimal water status is maintained throughout the life cycle of the crop. However, mild or relatively brief stress can usually be compensated for faster growth under favourable conditions (Major and Hamilton, 1978).

Sweet corn, on the other hand has a relatively high water usage (amount of water used to carry out an activity) and dry conditions at critical growth stages may adversely affects its yield (Wolfe et al., 1997). Short periods of drought during the reproductive phase can slow silk elongation, delay pollen shed, and thus negatively affects the synchrony between pollen shed and silking receptivity for fertilisation (Wolfe et al., 1997; Wolfe et al., 1988). A more detailed discussion of water use by maize and sweet corn is given in Chapter 6.

Under New Zealand conditions, Reid et al. (2001a; b) reported that water deficits, or drought, reduce the yield of both maize and sweet corn crop in a predictable manner. The authors reported that for maize and sweet corn, the yield is reduced when the available soil water content drops below 50 to 60% of the total available water holding capacity of the soil. In many soils of silt loam texture this gives a threshold value of 90 mm of available water, or deficit, after which further deficit starts to reduce yield. Highly predictable reductions in sweet corn biomass and yield under water deficit conditions have been reported (Stone et al., 2001). More detailed discussion of this is in Chapter 3 and 6.

2.4.3 Nitrogen (N) and Phosphorus (P)

The total quantity of N and P accumulated in a crop gives an indication of its N and P requirements provided 'luxury' amounts of these nutrients have not been supplied. N limitation may reduce demand for P in maize (Arnon, 1975). The N and P requirements of maize and sweet corn are dependent on the level of attainable yield and, therefore, depend on climate, characteristics of the soil and crop management practices. Districts differ substantially in their yield potential mainly because of variations in climatic conditions. Differences in soil fertility influence the amounts of N and P taken up by maize plants but do not markedly affect the seasonal patterns of uptake and distribution of these two elements in the plant (Hanway, 1962). However, management practices, e.g. timing of cultivation, rainfall/irrigation and the time of application of fertiliser may influence the pattern of nutrient accumulation. Fertiliser applications should be timed to take account of plant demand for various nutrients during the growing period.

2.4.3.1 N requirements and uptake

Maize and sweet corn yield/production is limited by N deficiency more often than by any other nutrient. Both cultivars (maize and sweet corn) partition more N to their grain than any other nutrient derived from soil (Steele et al., 1982; Marschner, 1986). Therefore, a good supply of plant available N is needed to meet plant growth and yield (Anderson et al., 1985; Nel et al., 1996; Reid et al., 2001a; b). The amount of N accumulated is influenced by the general nutrient status of the soil. For example, Arnon (1975) showed that the total N uptake by maize under extreme N-deficiency was 35

kg/ha, 158 kg/ha under K deficiency, 160 kg/ha under P deficiency and 198 kg/ha with adequate N, P & K supply.

The requirements of maize and sweet corn for fertiliser N vary greatly from field to field. Many existing N fertiliser recommendations in New Zealand are based on grower experience, fertiliser history and the number of years a field has been continuously cropped (Steele et al., 1982). The general recommended level of N application for maize in New Zealand is 200 kg N/ha in three split doses (Munir, 2000). For sweet corn, the current agronomic practice involves the use of between 100 kg and 150 kg N/ha incorporated into the soil in two applications (Hansen, 2000).

Literature shows that under conditions of adequate soil N, the N is taken up by maize plants throughout the season, relatively slowly during first month (establishment) and faster during the next month i.e. vegetative stage (Berger, 1962; Hanway, 1962). Sayre (1955) found a maximum rate of N absorption of more than 4.5 kg N/ha per day during the tasselling and silking stage. Similarly, Thom and Watkin (1978) reported the maximum rate of N uptake occurred during the period of intensive vegetative growth prior to tasselling when it exceeded 4 kg/day/ha. A similar trend of N uptake throughout the entire season by maize plant was reported (Aldrich and Leng, 1969; Ritchie, 1997).

It is also reported that N requirements vary at different stages of development of maize plant. Demand is minimal in the early stages, increasing as the rate of growth accelerates, and reaching a peak during the period between the onset of flowering and early grain formation (Arnon, 1975). It has been shown that maize draws nutrients most heavily from the soil from about 10 days before tasselling until about 25 to 30 days after tasselling (Sayre, 1948 as cited by Berger, 1962). Relatively high nutrient concentrations in the plant are necessary for maximum growth during the vegetative growth period. After vegetative growth and during grain formation, much of the N is remobilised and translocated from vegetative parts of the plant to the grain. Berger (1962) reported that at low soil fertility status (not stated any values), larger proportions of many nutrients in other plant parts will be translocated to the grain, whereas, at high soil fertility status, there will be less translocation of nutrients. The leaves hold a large share of the N that is taken up before tasselling. Although the leaves comprise only 12 to 14 % of the dry matter produced, more than 30% of the total N taken up is contained

in the leaves before translocation to the grain begins. At maturity about two-thirds of the total N in above ground parts of the plant is in grain, and about one-third in the rest of the plant (Berger, 1962). Sayre (1955) reported 162 kg N/ha was taken up by maize crop of 14 t/ha dry matter yield. This is a low yield compared to current yields expected for modern cultivars grown in New Zealand. In New Zealand, Steele (1985) reported 153 kg N/ha was removed in 12 t of maize grain (14% moisture). Reid et al. (2001a) reported that a typical maize crop requires an absorption of about 450 kg N/ha, with approximately 275 kg N/ha removed in the grain for a 15 t/ha grain yield. Thus, this gives a reported range of 12.8 to 18.3 kg N/tonne removed in maize grain for experimental plots in New Zealand.

When sweet corn is grown in New Zealand under suitable conditions, the above ground N accumulation of sweet corn can range from 130-240 kg N/ha (Hanly, 2001). Hansen (2000) reported N accumulation range of 125-225 kg N/ha in high yielding sweet corn crops (20-23 t/ha). Reid et al. (2001b) reported that a typical sweet corn crop carrying 25 t/ha of cob fresh yield requires an absorption of about 180 kg N/ha in the whole plant at cob harvest. There is no data indicating the amount of N removed in fresh cob. Obviously commercial yields of maize and sweet corn will require large amounts of soil mineral N or fertiliser N prior to vegetative growth and cob filling. The high relative mobility of nitrate in soil means that the incidence of rainfall (or irrigation) and drainage events will need to be considered in maintaining adequate N supply during crop growth.

2.4.3.2 P requirements and uptake

The effects of P on maize and sweet corn yield/production are substantial, but less clearly quantifiable than those of N. Both cultivars (maize and sweet corn) need P for their maturity and ultimately for grain formation. Therefore, a good supply of plant available P is needed to meet plant growth and yield (Steele et al., 1982; Anderson et al., 1985; Reid et al., 2001a; b). Like N, the amount of P accumulated also depends to an extent on the general nutrient status of soil. The requirements for maize and sweet corn for fertiliser P also vary greatly from field to field depending on the soil P fertility. Existing P fertiliser recommendations in New Zealand are based on results of field trials in different districts. The approach used to obtain these recommendations were the estimation of optimum (non-yield limiting) values for Olsen P test. The optimum Olsen

P test values were the values at which maximum yield appeared to be achieved. The existing Olsen soil test target levels, and therefore fertiliser recommendations (New Zealand) for maize and sweet corn differ greatly.

The recommended levels of P application for growing maize in New Zealand are 50 kg P/ha as pre-plant and 20-35 kg P/ha as a starter fertiliser if the Olsen P test value is < 11 mg P/kg (Steele, 1985). But if the Olsen test value is between 11-14 mg P/kg, then recommendations are to apply maintenance P only (Steele, 1985). In contrast, the experiments conducted across North Island by Reid et al. (2001a) found no response to P fertiliser at soil test values as low as 8 mg P/kg, and Reid et al. (2001a) some findings were consistent with Steele's experiments (Steele et al., 1981). There is no doubt that the soil test results vary within a paddock of course, and so if the average Olsen P value is 10 mg P/kg, there will be some areas where P is less than 8 mg P/kg. Therefore, Reid et al. (2001a) recommendations are to minimise the chances of these areas affecting the overall paddock yield, while maximising the chances that the fertiliser use is profitable. Hence, the recommended level of P application for maize by Reid et al. (2001a) is that if soil test P is greater than 10 mg P/kg, then no P fertiliser should be necessary. But if the soil test P value is <10 mg P/kg, then 20-35 kg P/ha is applied as a starter fertiliser to avoid nutrient deficiency. The authors also suggested use of a rapidly available form of P, such as superphosphate because it is quicker acting than other phosphate fertilisers (During, 1972). In contrast, to grow sweet corn, the recommended target Olsen P test values range from 28 to 35 mg P/ kg (Clark et al., 1986; Prasad et al., 1988; Reid et al., 2001b). Moreover, if Olsen P test values are less than 26 mg P/kg then 35 kg P/ha is recommended to be applied as a starter P fertiliser to grow sweet corn (Reid et al., 2001b). Evidence for differences in maize and sweet corn P requirements will be discussed further in section 2.5.

Like N, the pattern of P accumulation in the plant will also vary to some extent with nutrient levels of the soil. Again, relatively high nutrient P concentration in the plant is necessary for maximum growth during the vegetative growth period. The detail on maize plant P concentration limitations have already been discussed in section 2.4. For maize and sweet corn, the tissue P concentration is around 0.2% of crop dry matter (Reid et al., 2001a; b) and is generally stable over the vegetative growth and cob filling periods and consequently P supply is required during periods of rapid growth.

There is continuous uptake of P by maize plants during the growing season, though up to the commencement of flowering only 15% of the total quantity of P required is absorbed (Berger, 1962). Studies have shown the trend of P uptake by maize plant throughout the entire season (Aldrich and Leng, 1969; Ritchie, 1997). During grain formation, P translocation to grain is very similar to that of N. P is removed first from husks, cob and shank, then from the stalks, tassel and leaf sheaths, and last from the leaves (Berger, 1962). At maturity about three-quarters of the total P in the above ground parts of the plant should be in grain (Berger, 1962). However, N-deficiency has a marked effect in this respect, reducing P uptake. The literature shows that the total P uptake with maize under extreme N-deficiency was 10 kg/ha; of K-deficiency 29 kg/ha; of P deficiency 23 kg/ha, and of adequate N, P & K supply 33 kg/ha (Arnon, 1975).

In New Zealand, Steele (1985) reported 40 kg P was removed in 12 t grain (14% moisture) yield. Reid et al. (2001a) reported that a typical 15 t/ha maize grain crop absorbs about 65 kg P/ha with approximately 45 kg P/ha residing in the grain at harvest. A typical 25 t/ha fresh cob sweet corn crop absorbs about 24 kg P/ha (Reid et al., 2001b). Under suitable P conditions (Olsen P = 11- 45 mg P/kg), the above ground P accumulation of sweet corn ranged from 11-19 kg P/ha (Hanly, 2001). New Zealand field trials and reports (Steele, 1985; Reid et al., 2001a; b) show that the yield responses of maize and sweet corn to P fertiliser are rare unless the Olsen P values in the soil are less than 10 mg P/kg for maize and 26 mg P/kg soil for sweet corn crop.

2.4.4 Nutrient P use efficiency

The definition of nutrient efficiency often depends on the discipline of the researcher/scientist using this term. For example, a soil scientist may define nutrient efficiency as the amount of nutrient taken up per unit area of soil by a plant relative to the amount of nutrient in, or added to, the soil (external P efficiency or uptake efficiency). A plant physiologist may define nutrient efficiency as the relative growth of a plant per unit mineral nutrient taken up (internal P efficiency or P use efficiency) (Clark, 1990). In soil science terms the higher recommended target Olsen for sweet corn (section 2.1) than maize may suggest that sweet corn is less P efficient than maize.

Fohse et al. (1988) describe P efficiency as the ability of a plant to produce a certain percentage of its maximum yield at a certain level of soil P. According to Fohse et al. (1988), P efficiency is often expressed as the external P requirement i.e. the P content in soil required to produce 80% of maximum yield. Blair (1993) and Trolove et al (1996) related that P efficient plants arise because of either P uptake efficiency, which is the ability of plants to acquire P from the soil, or from P use efficiency (internal P efficiency), which is the ability of plants to utilise P in the shoot for the production of dry matter. Efficient P uptake by plants is enhanced by root characteristics such as long roots resulting in a large root surface per unit of shoot growth (Schenk and Barber, 1979, 1980). Small root diameter and especially long root hairs improve the acquisition of P from soil (Barber, 1995; Jungk, 2001; Trolove et al., 2003). Lynch and Brown (2001) demonstrated that root systems with enhanced root length in the top soil acquire P more efficiently than others of equivalent size. Therefore, the root morphology of a plant has a significant role in relation to P use efficiency. Research on P efficiency and its application to identify species and cultivars differences is well documented (Fohse et al., 1988; Anuradha and Narayanan, 1991; Zoysa et al., 1999; Hedley et al., 1994; Trolove et al., 1996; Alves et al., 2001; Ortiz-Monasterio et al., 2002; Dechassa et al., 2003; Trolove et al., 2003).

Literature also shows that plant species and even varieties of the same species may differ in their ability to grow in soils low in P availability (Fohse et al., 1988; Caradus, 1994; Trolove et al., 1996). For example, Trolove et al. (1996) conducted a glasshouse pot experiment that compared P use efficiency for lotus and three genotypes of white clover growing on rock phosphate soil, Olsen P of 11 mgP/kg soil. They found that lotus had higher internal P efficiency (340 mg DM/mg P) than three clover genotypes (240 mg DM/mg P), as lotus produced higher dry matter (DM) than clover per unit P taken. Dechassa et al. (2003) in another experiment (glasshouse) compared P efficiency of cabbage, carrot and potato (on soils with Olsen P of 16 mg P/kg soil) and reported that cabbage (769 mg DM/mg P) had high P efficiency than potato (370 mg DM/mg P) as cabbage produced higher DM per unit of P taken. Alves et al. (2001) evaluated twelve maize hybrids in nutrient solution (0.3, 0.9, 2.7 and 5.4 mg P/L) to identify P efficient maize hybrids and found significant differences amongst hybrids in P efficiency. Their results were based on changes observed in root length rather than calculating the internal P efficiency. They did not study sweet corn (for more detail see Chapter 4).

In conclusion, there are several ways in which nutrient use efficiency can be expressed. Phosphorus use efficiency has been defined by some scientists as the efficiency with which a plant genotype accumulates P at a given level of soil, whereas other workers emphasised as the amount of dry matter produced per unit of P accumulated. Extensive information is available on maize P uptake and efficiency, but there is little published work on sweet corn. Therefore, in relation to maize and sweet corn comparison, it is proposed that phosphorus use efficiency will be measured in field crop, with a comparison between two cultivars.

2.5 Maize and sweet corn fertiliser P response studies

In New Zealand, the recommendations for sweet corn indicate a high soil P status compared with maize, therefore, this section reviews reports of experiments measuring yield responses to either fertiliser P applications or changes in soil P test values for both cultivars from overseas and New Zealand.

The response of maize to P fertiliser is not large compared with that to N fertiliser, because N deficiency places a larger constraint on yield than P deficiency (Steele, 1985). Marked N responses will be obtained on soils that have been intensively cropped in the past, however, P response will depend more on previous fertiliser history because much less P is removed with the crop in harvesting. After several years of fertilisation with P, growth response to further P fertiliser may become negligible, as a result of a cumulative residual P accumulation. Soil test P status is a significant determinant for P fertiliser application and variations in soil P status are reflected in fertiliser recommendations, for growing maize, that vary from a low rate of 6 kg P/ha to rates as high as 50-60 kg P/ha (Arnon, 1975).

2.5.1 Maize P response studies

Bishop et al. (1972) conducted fertiliser trials (NPK) with hybrid maize on six soil series at 14 locations for a 6 year period (1964-1969) in Canada. The range of Olsen P tests in those experiments at 14 locations was from 3 to 100 mg P/kg. They found the effect of N on both leaf composition and yield were predominantly linear and much greater than the effect of either P or K. In the case of yield, there was an effect from N

at 10 locations, P at four, and K at one. In their experiments, the yield responses with P to maize leaf growth occurred when pre-plant Olsen P values were low (3 or 9 mg P/kg), but not at higher Olsen P values. From those results, they suggested that N, P and K at 100-150, 30-45, and 30-40 kg/ha were generally adequate for maize growth.

To document the role of P availability in leaf growth and senescence dynamics in maize, Colombo et al. (2000) conducted 3 year field experiments (1995-1996) in France with low, moderate, high and very high soil test P levels (Table 2.6). The treatments were P0 (no P since 1968), P1 (17.5 or 11 kg P/ha/year), P2 (35 or 22 kg P/ha/year), P3 (79, 33, or 22 kg P/ha/year). Data were recorded from emergence to silking. The P0 treatment (2.8-3.1 mg P/kg soil) produced P deficiency symptoms in leaf appearance and reduced the final area of leaves located below the main ear by 18 to 27%. The expansion and growth dynamics of upper leaves were little affected by soil P level. Overall, the whole plant peak green leaf area was 16% lower under P stressed conditions until 550 degree days and peak leaf area was reached significantly later. Compared with plants with no P stress, P stressed plant growth rates were reduced by 15 to 33% during most of the grain filling period. Their finding suggests that P plays a key role in the morphogenetic and leaf expansion processes in maize development. The major reduction in leaf area occurred when Olsen P test values were < 7 mg P/kg soil. Colombo et al. (2000) concluded that P deficiency decreased plant biomass accumulation by limiting interception of photosynthetically active radiation (PAR) rather than reducing efficiency of conversion of PAR into dry matter.

Plenet et al. (2000a; b) reported the results of their field trials conducted during 1995-1997 for leaf growth, radiation use efficiency, biomass accumulation and yield components of maize field crops under P deficiency condition in Europe. In their experiments, three P fertilisation treatments were applied, P0 treatment (0 kg P/ha/year since 1972), P 1.5, which was 1.5 times the amount of P exported annually from the field by grains (42.8 kg P/ha/year) and P3, equal to 3 times the amount of P exported annually from the field by grains (94.3 kg P/ha/year). The treatment P1.5 corresponded to the P fertilisation rate applied by farmers in that area, and was used as the control treatment. The application of P fertiliser i.e. P 1.5 & P 3 treatments showed significant increases in soil P levels compared with the P0 treatment. They reported that in 1995, the Olsen P in the top layer (0-25 cm) was 23 mg P/kg in P0, 49 mg P/kg in P 1.5 and

66 mg P/kg in P 3 treatments. In that sandy soil, 23 mg P/kg of Olsen P was considered to limit growth because during the last 15 years, the grain yield was about 10-12% lower in the P0 treatment. They reported that the leaf area index (LAI) was significantly reduced in the P0 treatment compared with the P1.5 and P3 treatments, especially during the first phases of the crop cycle (up to 60% between the 7 and 14 visible leaves stages). This effect gradually decreased over time. The lower LAI was due to two main processes affecting leaf growth. The final number of leaves per plant and leaf senescence were only slightly modified by P deficiency. However, the leaf elongation duration was not greatly affected by P treatments. Similar to Colombo et al. (2000), Plenet et al. (2001a; b) demonstrated that the impact of P deficiency on maize growth was mainly the consequence of the negative effect of P deficiency on leaf growth and its subsequent effect on photosynthetically active radiation (PAR) absorption. The negative effect of P deficiency on leaf growth was mainly observed at the early stages, which was consistent with numerous other observations which have emphasised the need for P starter fertilisers for maize (Barry and Millar, 1989; Gavito and Millar, 1998).

Table 2.6 Annual P dressings applied in four treatments of a field experiment and Olsen P test values in the topsoil (0-30 cm) taken in January 1995 and 1997 prior to growing maize.

	Experimental P Treatments			
Years	P0	P1	P2	P3
	Annual P dressing (kg P/ha)			
1968-1991	0	17.5	35	70
1992-1993	0	11	22	22
1994-1998	0	11	22	33
	Olsen P (mg P/kg)			
Mean (1995)	2.8	6.7	14.2	33.5
Mean (1997)	3.1	7.3	9.5	29.5

Source: Colombo et al., 2000

In New Zealand, several studies have investigated the nutrient requirements and fertiliser effects for maize grain production (Cumberland and Douglas, 1970; Steele and Cooper, 1980; Steele et al., 1981; Cornforth and Steele, 1981; Steele et al., 1982). The trials were conducted on sites which had previously been in pasture and cropping. N and

P fertiliser had very little effect on maize grain production in the first two crops following pasture (Cumberland and Douglas, 1970). Steele and Cooper (1980) reported no increase in grain yield from seven field trials conducted in North Island, when P fertiliser was added, even at an Olsen P test as low as 8 mg P/kg. In those field trials the pre-plant Olsen P test values ranged from 8 to 32 mg P/kg. Based on those results, they suggested that maize can be grown successfully without pre-plant fertiliser, however, application of only small amounts of N and P as starter fertiliser would be useful for crop growth. Steele et al. (1981) recommended that if the Olsen P test is 15 mg P/kg or above, no pre-plant P is required and only 20-25 kg P/ha are required as starter. It is also reported that yield was depressed when pre-plant P was applied to soils with an Olsen P test above 22 mg P/kg (Steele et al., 1981). Steele (1985) reported that on average, 116 kg N/ha, 69 kg P/ha and 56 kg K/ha were applied to maize crops in Waikato during 1982-83. This average amount of P applied (69 kg P/ha) was 173 % of that removed in a 12 t/ha grain crop. Of the 65 maize producers surveyed, 87% applied pre-plant fertiliser even though on 65% of farms the Olsen soil test was above the level at which application of pre-plant fertiliser was recommended. Moreover, 11% of maize producers applied P to soils having an Olsen test over 22, where yield depressions would be expected to occur. Finally, Steele (1985) reported their recommendations for growing maize in New Zealand based on soil test information as; i) Olsen P test is > 14, then do not apply pre-plant, but apply 20 kg P/ha in starter ii) Olsen P test is 11-14, then do not apply pre-plant and apply the amount of P in starter that will replace the P removed in grain, iii) Olsen P is < 11, then apply 50 kg P/ha pre-plant and 20-35 kg P/ha in starter depending on expected yield.

More recently, after conducting field trials at twelve locations in different regions across the North Island (i.e. measurements made on single maize cultivar in 1996-1997, three maize cultivars during 1997-1998 and on commercial maize crops grown by growers according to their usual practices in the 1997-1999 season), Reid et al. (2001a; and 2002) suggested that no P fertiliser application is needed when Olsen P is greater than 10 mg P/kg and an application of 20-35 kg P/ha as starter is required only when Olsen P is less than 10 mg P/kg. The Olsen P test values in those field trials (12 locations) ranged from 7 to 42 mg P/kg, and the grain yields varied from 4 to 18 t/ha (Reid et al., 2002). No response to P fertiliser occurred even at soil P test values as low as 8 mg P/kg (Reid et al., 2001a). The maize data collected from those 12 sites were used to calibrate

the computer simulation model PARJIB (detail of PARJIB model in section 2.5.2) to forecast cereal yield responses to nutrients. Based on those results and analysis using the model Reid (2002) and Reid et al. (2002) reported that yield responses to P fertiliser are rare with maize under New Zealand conditions unless the Olsen P levels in the soil is less than 10 mg P/kg. Finally, they suggest that if Olsen P test is greater 11 mg P/kg, there is no need to apply any additional pre-plant or starter P fertiliser to grow maize crop in New Zealand.

2.5.2 Sweet corn P response studies

Overseas studies suggest that sweet corn may be more responsive to P than maize (Bole and Freyman, 1975; Sanchez et al., 1991). Table 2.7 shows fertiliser P response studies for sweet corn from overseas and New Zealand and the P fertiliser rates applied during the experiments. The results are discussed below.

Bole and Freyman (1975) conducted three separate field trials in the season 1971-72 (not head to head) examining the response of irrigated maize (field corn) and sweet corn to N and P fertilisers in Canada on a Brown Chernozemic soil, Cavendish loamy sand with low mineral nitrate-N (5 to 10 mg N/kg) and moderate to high level of Olsen P levels (20 to 30 mg P/kg) in the 0-15 cm soil depth. They reported that both cultivars responded primarily to N, with only limited responses to P. Total dry matter yields responded more to higher levels of N than did grain yield. Maize (field corn) was more responsive to N fertiliser than sweet corn. Yield was slightly lower (but not significantly) with no P fertiliser treatment compared with P fertiliser applications of 15 kg P/ha or higher. During this two year field study, the P fertiliser significant responses in sweet corn kernel (average P treatments 10 t/ha) and ear yield (average P treatments 20 t/ha) were observed only in one of the field trials; no growth responses to P occurred in the other two trials. The authors reported that the limited response to P was probably due to the moderate to high levels of residual fertiliser P available in soil. However, their study has shown that sweet corn was more responsive to added P than was maize.

Bar-Yosef et al. (1989) conducted a field experiment on a loessial soil with a high Olsen P value (0.8 mmole P/kg soil i.e. 25 mg P/kg value) to test the hypothesis that placement of P fertiliser through subsurface irrigation emitters is more effective in

stimulating P uptake than surface placement. In their experiment, four concentrations of P in irrigation water (0.04, 0.16, 0.64, and 1.29 mol P/m^3) were applied via surface or subsurface emitters to sweet corn, and marketable cob yield increased with P concentration, yielding 22.9, 24.3, 24.9, and 28.9 t/ha, respectively. They reported that the sweet corn yield was higher for tricklers placed 30 cm below soil surface (25.2 t/ha) than on the surface (23.5 t/ha). They concluded that the elevated sub-irrigation P concentrations increased the soil solution P concentration, thereby increasing total P uptake and total dry matter production by the plants. The deep trickler placement significantly increased the fraction of total dry matter allocated to the ears, which resulted in higher marketable yield.

Table 2.7 Fertiliser P response field studies for sweet corn (overseas & New Zealand).

Country (Source)	Soil P status range (Experiments)	Experimental Treatments (P fertiliser rates)	Summary of results in field trials
Canada Bole &Freyman (1975)	20-30 mg P/kg (Olsen P)	9 P rates 0,7.5,15,22.5,30,37.5,45, 52.5, 60 (kg P/ha)	P deficiency decreased kernels & ears yields in 1971 at Cranford site, but no response to kernels/ears in 1972)
Israel Bar-Yosef et al. (1989)	0.8 mmol P/kg soil (Olsen P= 25 mg P/kg)	4 P irrigation rates 0.04, 0.16, 0.64,1.29 (mol P/m^3)	P deficiency decreased dry matter, P uptake & cob yield
USA Sanchez et al. (1991)	0.21 – 3.47 g/m3 (2-29 mg P/kg)	5 P rates 0, 23, 50, 75 &100 (kg P/ha)	P response to sweet corn when soil test P levels were < 1.2 g/m^3 (Olsen P =10 mg P/kg) (Ears yield increased).
China Wu et al. (1993)	6 mg P/kg (Olsen P)	2 P rates 0 and 65 (kg P/ha)	P deficiency decreased total yield
New Zealand Fletcher &Moot (2003)	6 mg P/kg (Olsen P)	5 P rates 0,50, 100, 150, 200 (kg P/ha)	P deficiency delayed maturity of sweet corn (total yield not reported).
New Zealand Fletcher et al. (2002)	6 mg P/kg (Olsen P)	5 P rates 0,50, 100, 150, 200 (kg P/ha)	P deficiency slowed canopy development, solar radiation, decreased leaf appearance rates (yield not reported).
New Zealand Fletcher (2005)	6 mg P/kg (Olsen P)	5 P rates 0,50, 100, 150, 200 (kg P/ha)	P deficiency decreased kernel yield & biomass
New Zealand Prasad et al (1998)	10-18 mg P/kg (Olsen P)	5 P rates 0,50, 100, 150, 200 (kg P/ha)	P deficiency decreased total sweet corn yield

Another study by Sanchez et al. (1991) comparing relative efficiency of broadcast and banded P fertiliser for sweet corn produced on histosols soil in Florida and reported that sweet corn responded to P only when soil test P levels (water-soluble P test) were below 1.2 g/m^3 (approximately Olsen P of 10 mg P/kg). Their field trials were conducted across six sites during 1988 and 1989 and broadcast and banded P rates were 0, 25, 50, 75 and 100 kg P/ha. In their six experiments (1988-89), the total marketable yields of sweet corn ears were increased by P rates and affected by placement in four of the six sites experiments. In two sites no responses to P were noted or observed.

Wu et al. (1993) reported the results from their field trial (June-Sept, 1988) in China on yield and kernel composition response of sweet corn to added combinations of NPK fertilisers. This study was conducted on a soil P with Olsen P test value of 6 mg P/kg. They found significant effect of fertiliser NPK on all sweet corn growth parameters (plant height, leaf number, stem diameter, leaf area and total yield produced). All these measured parameters were higher under a combined NPK application of 150 (N), 65 (P) and 65 (K) kg/ha compared with the treatment where no NPK fertilisers were applied. In this study, the authors concluded that N was the main factor which stimulated the growth of sweet corn. However, N and P together also contributed towards higher yield than recorded with K interaction. The total sweet corn yield was 8.8 t/ha under 65 kg P/ha with 150 kg N/ha treatment compared with 7.7 t/ha under 0 kg P/ha with 150 kg N/ha treatment. No report on climatic condition during the experiment period was made. The soil in the experiment site was a Red Clay with a pH of 4.5, which is below the pH values recommended for growing sweet corn or maize crop.

Fletcher and Moot (2003) and Fletcher et al. (2002) conducted field trials on very low soil P status sites (Olsen P value of 6 mg P/kg) to examine fertiliser P response to sweet corn at Lincoln in Canterbury, New Zealand. Five P fertiliser treatments (0, 50, 100, 150 and 200 kg P/ha) were used in their field trial. This study was to investigate how radiation interception by sweet corn and associated processes (leaf appearance and individual leaf area) responded to the above five fertiliser P levels. Fletcher and Moot (2003) reported that P deficiency delayed maturity in sweet corn (hybrid Challenger) but N had a minimal effect on maturity. They also found that P deficiency affected both individual leaf size and leaf appearance rate. Fletcher (2005) at the same low P site used (Fletcher et al., 2002) reported increase of both kernel yield and crop biomass to

increasing P supply. In two seasons where experiments were conducted, there was 1.1 t/ha less kernel mass when no P fertiliser was supplied.

Previous overseas and New Zealand field trials evaluating sweet corn yield response to P do not appear to provide equivalent evidence that sweet corn requires a higher soil P status to maize (Table 2.7). However, very few New Zealand studies have been conducted to evaluate sweet corn growth response to P fertiliser in field. The current recommendations for higher target Olsen P test values to grow sweet corn may be derived from the fact that sweet corn is treated or considered as a high value vegetable crop. Fertilisation of high value vegetable crops in New Zealand is based on avoiding risks of nutrition limiting the yield of marketable produce. It is common for fixed fertiliser rates to be quoted for each vegetable crop (Wallace, 1975, as cited by Prasad et al., 1988). Phosphorus fertiliser recommendations for vegetables are usually high and based on target soil test values (McLean, 1977; Cornforth, 1998). The target soil test value can be defined as the value required at the time of sowing so that 95% of maximum marketable yield can be reached at harvest time (Prasad et al., 1988).

Prasad et al. (1988) reported the results of twenty-two field experiments conducted during 1967-1984 under New Zealand field conditions to determine target soil test P values for a range of twelve vegetable crops including sweet corn. All experiments were conducted at one location on a Levin silt loam with initial Olsen P test values ranging from 10-18 mg P/kg and high P retention characteristics (Anon, 1979). The different levels of soil P were achieved by applying and incorporating to 15 cm soil depth rates from 0 to 15 tonnes P/ha (superphosphate) in two lots, 2-3 weeks apart. Yields were regressed against soil P values and target values were calculated as the P values giving 95% of maximum yield. In their experiments, they found sweet corn yield response to P fertiliser and therefore reported the target Olsen P levels of 29 mg P/kg based on 1967/68 experiment and 27 mg P/kg based on 82/83 results to grow sweet corn in NZ.

Reid et al. (2001b) also recommended higher Olsen P test values to grow sweet corn than maize. They suggested that if the soil test P is greater than 35 mg P/kg, then P fertiliser is unlikely to improve yield; if soil test values are 26-35 mg P/kg, P fertiliser may increase yield slightly, but such applications are unlikely to be profitable. Furthermore, the authors also suggested that if Olsen P is less than 26 mg P/kg, then 35

kg P/ha of P fertiliser is recommended to be applied as a starter fertiliser. Reid et al.'s (2001b) recommendations for sweet corn growing are based on calculated optimum yields achieved by using the PARJIB model (Reid, unpublished results, cited by Reid, 2002). A version of PARJIB have accurately predicted yields of maize, and a number of other vegetable crops, including sweet corn, tomatoes and carrots (Reid, 2002). PARJIB uses inputs of daily air temperature, rainfall/irrigation, radiation, potential evapotranspiration and soil information (estimates of available water capacity and soil chemical analyses) plus an estimate of maximum potential yield to predict the actual growth rate of the crop (for detail see Reid, 2002 and Reid et al., 2002). The crop response to nutrient supply is calculated by comparing actual supply of nutrients from the soil to the plant demand for nutrients to produce maximum yield. The model accounts for interactions between nutrients, and the nutrients most considered to affect yield are N, P and K; and other nutrients are assumed to be adequate supply (for detail see http://www.crop.cri.nz). Therefore, attainable sweet corn yield is estimated from potential yield and limiting conditions are applied via the PARJIB model. Although the model provides an "expert system" to encapsulate current knowledge on the responsiveness of sweet corn growth, the knowledge it uses appears to be derived solely from the trials of Prasad et al. (1988) and Reid unpublished field data (Reid, 2002).

2.6 Maize and sweet corn root systems and P uptake

2.6.1 P uptake and root system characteristics

Plant roots are important for anchoring the plant, synthesis of growth regulators, water and nutrient absorption, and metabolizing photosynthate for root growth (Barber, 1984). Almost all mineral nutrients absorbed by plants are primarily supplied to the plant by absorption through the root system (Barber, 1984). Therefore, the three main roles of root systems are anchorage, water absorption and nutrient uptake. The limiting factor in P uptake by roots from soil is the diffusion of P to the root surface (Tinker and Nye, 2000). About 90 to 98% of P movement in soil is by diffusion (Barber, 1980). P moves only limited distances from its source estimated to be about 5 mm (Barber, 1976). There is a very small soil P depletion zone around a root, thus the extent of P uptake is very dependent upon root surface area and new root length exploring areas of fresh soil P where P has not been depleted.

Lack of P movement to roots suggests that P efficient root systems must be those that; explore larger unit volumes of soil per unit root mass or zones of soil that have higher P status in soil adjacent to the root. P efficient roots will also have active P acquisition processes, for example recent research by Rausch and Bucher (2002) indicates that plant roots take up and transport phosphate anions via membrane-associated protein. Literature also shows that the architecture of root system is related to its water and nutrient uptake (Pages and Pellerin, 1994). Pages and Pellerin (1994) studied the root system architecture in field grown maize (in France) and underlined the quantitative importance of the lateral root length at the root system level, and their predominant role in nutrient absorption. Lynch and Brown (2001) reported that P uptake by plants is enhanced by root characteristics (root number, length and diameter). Recent research has pointed out that root longevity (rate of turnover) may significantly influence nutrient uptake (see review by Wu et al., 2005). The role of soil water in P uptake also remaining in the light of recent evidence that root systems can continue to taking up of nutrient (P) even under dry soil conditions (Bernd et al., 2002). The authors proposed that under dry conditions, water and root mucilage's absorb sufficient amount of water, which facilitates P uptake (more detail about this is in Chapter 6). Thus knowledge of plant root system and their development in soil is extremely important for understanding P nutrition of field crops (more detail information in Chapter 5).

As mentioned above, P uptake is dependent on the root system (root number, length and surface area) in contact with the soil (Anghinoni and Barber, 1980; Pages and Pellerin, 1994; Lynch and Brown, 2001; Wu et al., 2005). However, the concentration of P in the soil may also influence root morphological characteristics such as root diameter, root length, lateral root formation, and root surface area (Schenk and Barber, 1979; Zhang and Barber, 1992). It is also reported that small root diameter and long root hairs also improve the acquisition of P from soil (Jungk, 2001; Trolove et ., 2003). Authors generally agree that P deficiency leads to a higher root-to-shoot ratio (Anghinoni and Barber, 1980; Khamis et al., 1990; Rosolem et al., 1994; Trolove et al., 2003). Therefore, the ability of a genotype to increase root surface area in response to soil P levels could help support high rates of P uptake during early stages of growth. It is also reported that there is significant genetic variation in P uptake, accumulation and use in maize varieties (Clark, 1983), so it is possible that variation in root system characteristics could result in sweet corn requiring more P fertiliser than maize to grow.

2.6.2 Role of mycorrhiza fungi in P uptake

It is important to consider that the root surface area of maize and sweet corn could be extended by formation of mycorrhiza. A mycorrhizal association is a symbiotic relationship between plant root system and particular fungus that colonize the cortical tissue of roots during periods of active plant growth (Stevenson and Cole, 1999). Mycorrhizas are widespread under natural field conditions and occur with many agricultural crops (Abbott and Robson, 1982). Depending upon the plant and types of fungal species, mycorrhizas are commonly grouped into two major types i) Ectomycorrhizas, which are characterised by dense mycelial sheaths around the roots and intercellular hyphal invasion of the root cortex, and are limited to mostly temperate forest trees and ii) Endomycorrhiza, where the fungi exist external hyphal networks in the soil and grow extensively within the cells of the cortex; They are formed by nearly all plants (Bolan, 1991; Trolove et al., 2003). Specific types of endomycorrhiza are formed by members of the Ericoid and Orchidaceous mycorrhiza, but the most common type of mycorrhiza which is widely spread in plants are the vesicular-arbuscular mycorrhiza (VAM) (Clark, 1990; Bolan, 1991).

The effect of mycorrhizas in increasing plant growth has been documented by many researchers for different plant species (Smith, 1980; Tinker, 1978; Jensen, 1984) and reviewed (Bolan, 1991, Clark and Zeto, 2000; Gianinazzi et al., 2002). The most beneficial effect of mycorrhiza on plant growth has been related to increase in the uptake of nutrients, especially P (Bolan, 1991). The possible mechanisms by which mycorrhizal fungi increase the uptake of P by plants from the soil is shown by Trolove et al. (2003) (Figure 2.2). The possible mechanisms for greater P uptake with VAM association are extension of the root system (root length) to increase the P absorption surface area (Gerdemann, 1968; Drew, 1975; Berta et al., 2002), reduction of the diffusion distance for soil P (Rhodes and Gerdemann, 1975, cited by Clark, 1990), chemical modification of P sources to make the more available for uptake and transfer (Abbott and Robson, 1982), and modification of root properties for P uptake (Smith and Pearson, 1988).

Many cereal crops have enhanced growth and absorption of P from low P soils when roots are colonized with VAM (Krishna and Bagyaraj, 1981). For example, with no

added fertiliser P, VAM associations with roots enhanced growth equivalent to the addition of 25 kg P/ha of fertiliser in sorghum (Raju, 1986, cited by Clark, 1990) and 8 kg P/ha for pearl millet (Krishna and Dart, 1984). The addition of P to the soil reduced VAM infections and growth enhancements due to VAM (Raju, 1986, cited by Clark, 1990). Mycorrhizal sorghum plants had longer root lengths than nonmycorrhizal plants (Raju, 1986, cited by Clark, 1990). VAM colonised sorghum and wheat roots enhanced plant ability to withstand water stress (Ellis et al., 1985), but enhanced drought stress was not noted in maize (Hetrick et al., 1984). However, the ear leaf P concentration differences in maize were closely correlated to the percentage of VAM colonisation (Toth et al., 1984) and the high leaf P maize lines (>0.25%) had higher VAM colonisation's than low leaf maize lines (<0.25%) (Toth et al., 1984). Generally, VAM colonisation appears to be important in cereal crops for enhanced growth and P uptake especially when grown on low P soil conditions.

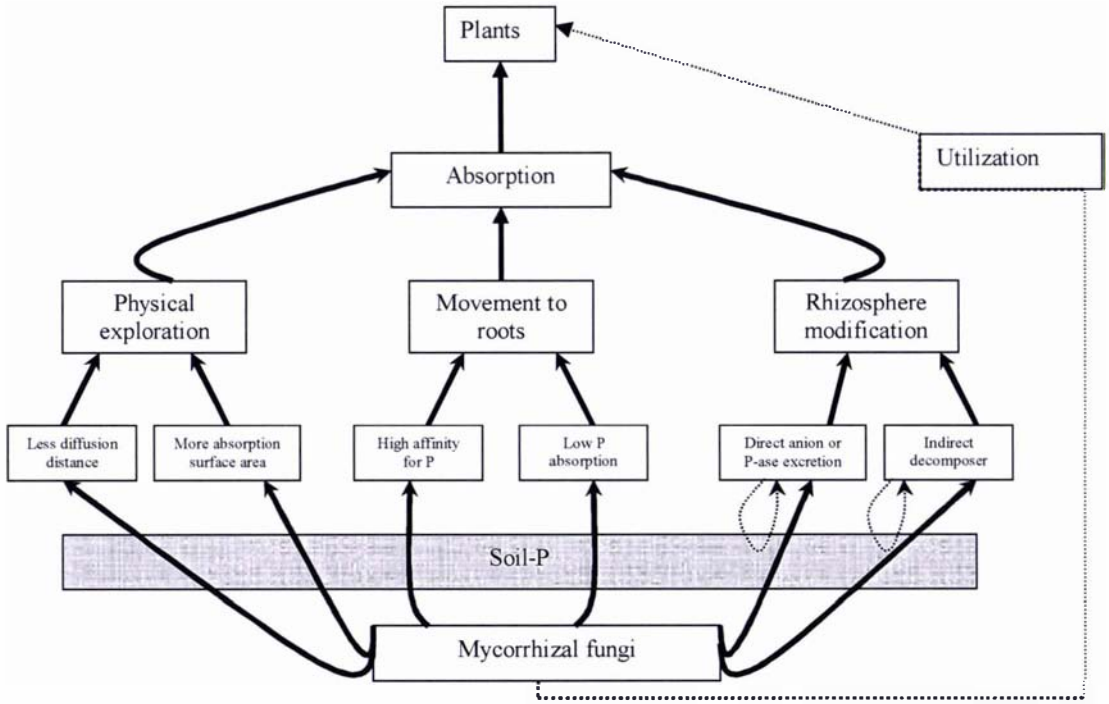


Figure 2.2 Possible mechanisms by which mycorrhizal fungi increase the P uptake by plants from soil (Redrawn from Trolove et al., 2003).

2.6.3 Root growth and development of maize and sweet corn

Depending upon the vascular system of plant species, root systems are commonly grouped into two major types i) monocotyledons ii) dicotyledons (Barber, 1984). Most cereal crops have monocotyledon rooting systems. The overall morphology structure of the maize and sweet corn root system is almost the same as that of other cereal crops, consisting of several seminal roots (Plate 2.3) that emerge from the seed and supply the seedling with water and nutrients during early growth. These may die after adventitious roots develop from transitionary nodes on the coleoptile (Barber, 1984). The seminal roots that emerge from the seed are laid down in the embryo, whereas the adventitious or nodal roots are formed later from underground and aboveground stem nodes.

Plate 2.3 Maize and sweet corn root system in the Manawatu experiment at 50 DAS during the season 2002-03 in New Zealand (by excavation technique)

The root system of sweet corn is very similar to that of maize but smaller (Plate 2.3). Maize has a widely spreading, deeply penetrating, and much branching root system. A lateral spread of 135 cm on all sides of plant is possible, and a root penetration depth of 150 to 180 cm is common, whereas in sweet corn a lateral spread of 90 cm around the plant is possible with a root depth equal to the height of the crop (Weaver, 1926).

Weaver (1926) studied maize and sweet corn root system (development) in loess soil in eastern Nebraska and reported that at 5 weeks old maize plants had seminal and adventitious roots almost to 30 cm in the soil profile. The roots were coarse, from 10-15 in numbers, about 1.5 mm thick and ranged in length from 2.5 cm to over 45 cm. At 8 weeks, a remarkable extension of the root system of maize plant (120 cm high) was observed. The main lateral roots were extended more than 120 cm from the base of stalk (stem). In addition to that, an entirely new group of roots were developed and penetrated vertically downward. The longest vertically penetrating roots grew at the rate of over 5 cm per day. Moreover, some roots were quite long and 3-4 mm thick. At that time, the roots of neighbouring stalks (stem), which were only 16 in apart, had greatly overlapped. At that stage, the roots of plants in adjoining rows 90 cm apart were drawing upon the same soil area for water and nutrients.

At 15 weeks, the root system of mature maize plant (240-250 cm high) was examined when a few older leaves had dried, but most leaves were still green. The husks on the ears were close to dry, and the kernels were dented. The crop had completed its root growth. The main lateral root system was not much increased compared with that found at 8 weeks. Most of the roots were found in the top 30 or 60 cm of the soil profile. Some retained a nearly horizontal position throughout their entire period, while others went at various angles for a few cm to 90 cm and then turned downward either abruptly or with a gentle curve. The longest roots extended to the 90-120 cm soil depths. Unlike the shallower portion of the root system, the more deeply penetrating part had made marked development, many roots extended from 180 to 210 cm deep, and a few up to 240 cm. Some of these deeply penetrating roots originated from brace roots. These were formed in whorls from the lower nodes above ground. They were covered with a mucilaginous substance which protected them from drying. Weaver suggested they performed the double role of anchorage and absorption (see more detail information is in Chapter 5).

The most rapid development of maize roots occurs during first 8 weeks after planting (Anderson, 1987). A study of field grown maize found that maximum size of the root system was reached 11 to 13 weeks after planting and decreased after 14 weeks (Mengel and Barber,1974). In contrast, in another field study, the estimated size of the maize root system at 8 weeks after planting was not significant different from the size at silking or harvest (Anderson, 1988). It is also reported that as the maize plant ages, root growth generally increases at a slower rate than shoot (Baligar, 1986) and after silking, root length declines (Mengel and Barber, 1974). The decline in root length after silking presumably is due to the high C demand of the ear, and the resulting translocation of C and N from the roots to ear (Wiester and Horst, 1993).

Mengel and Barber (1974) also reported the distribution of maize roots with soil depth in field situations. At 30 days after sowing, more than half of the maize roots were in the top 15 cm of soil profile, and this fraction dropped to 30% by plant maturity stage. Further, they found branch roots continued to extend downward into the soil and a larger portion of those roots were below 15 cm as plant growth increased. Overall, in their study, the consolidated soil below 75 cm restricted deeper root growth to provide more information. There are no equivalent measurements published for sweet corn.

2.6.4 Fertiliser P response studies on maize roots

The results from laboratory and field studies on maize root system response to P fertiliser (root length and biomass) are somewhat contradictory. Some studies reported increases in root length in response to P fertilisation, whereas others reported negligible change in root length under both laboratory and field conditions. Presumably native soil P status, moisture content and structure are some of the other important variables controlling these results. As mentioned above, the morphological properties of roots are important factors determining the uptake of less mobile nutrients P in soils. Therefore, it is important to highlight some studies of the root growth response to P fertilisation.

Anghinoni and Barber (1980) observed increased root length and dry weight in 12 day old maize plants that were subjected to P starvation for 1 to 6 days (Table 2.8). They reported that the placement of P stimulated root growth in the fertilised portion of soil as compared with root growth in the unfertilised portion. Narayanan and Reddy (1982)

Table 2.8 Laboratory studies on the fertiliser P response of maize root growth.

Source	P status (experiment)	Plant stage /age (experiment)	Root growth -ve (decrease)	P response + ve (increase)
Anghinoni and Barber (1980)	P solution	18 day old		√
Narayanan and Reddy (1982)	P solution	15 day old		√
Mackay and Barber (1985)	Bray P 55, 74,130 mg P/kg	28 day old		√ √
Baligar (1987)	P solution	22 day old		√
Hajabbasi and Schumacher (1994)	0,45, 300 mg P/kg	V6		√
Schenk and Barber (1979)	P solution	23 day old	x	x
Khamis et al. (1990)	Nutrient solution	22 days	x	x
Mollier and Pellerin (1999)	Nutrient solution	V5 stage	√	
Fusseder and Beck (1988)	-	20 days	x	x

observed on 15 day old maize plants more primary and secondary root length, but less tertiary root length when plants were grown in a nutrient solution without P. In another glass house study, both soil water and P level significantly affected the root length, root radius and total root surface of maize at 28 day growth period (Mackay and Barber, 1985). Similarly, Baligar (1987) also observed in 22 day old maize plants a greater root weight when plants were grown at low P concentration (100 µmol/L) compared with higher P concentration (1000 µmol/L). Some other studies have also reported a reduction of root growth under P deficiency (Hajabbasi and Schumacher, 1994; Rosolem et al., 1994).

In contrast, some studies have reported no response to P fertilisation. For example, Schenk and Barber (1979) observed almost no effect of the P fertilisation rate on root length and root weight of 23 day old maize plants (Table 2.8). Similarly, Khamis et al. (1990) also observed no effect of P deprivation on root biomass on 3 week old maize plants even after 22 days of P starvation. A further study reported that root growth was

slightly enhanced a few days after starvation, but was finally reduced (Mollier and Pellerin, 1999).

These contrasting results show that the root system response to P availability is complex and is likely to depend on the range of soil P availability, the time scale of the experiment and the root parameters under consideration. Moreover, most of the studies cited were conducted on young plants in pot experiments, so results may be influenced by the particular conditions of such experiments (low light, physical constraints for root growth, etc.). By contrast, information on the morphological response of the root system to P deficiency in field conditions is scarce. Under New Zealand conditions, no studies have been published on comparing maize or sweet corn root systems, or the effect of any nutrient including P on root biomass. However, some studies in New Zealand have reported root information for some cereal and horticultural crops (Gibbs and Reid, 1992), tomatoes (Reid et al., 1996), Kiwifruit (Reid et al., 1993) and pasture grasses (Matthew et al., 1986; Matthew, 1992; Sumanasena, 2003; Hepp, 2003). There is a need then to quantitatively compare in this study, the maize and sweet corn root systems and to examine how any such differences relate to P nutrition of these crops.

2.7 Techniques for measuring root systems

Measurement of the extent and development of plant root systems is important to understand nutrient and water uptake mechanisms. Root measuring techniques for field crops must be selected carefully in order to meet the requirements of documenting root system size and development.

Comprehensive reviews of various methods of studying root systems in different countries have been produced (Bohm,1979; Harper et al. 1991; Atkinson; 1991). These reviews cite more than 1000 references. Several studies have used different techniques to measure maize root systems (Bohm, 1976; Reid, 1981; Anderson, 1988; Kuchenbuch and Barber, 1988; Pages et al., 1989; Logsdon and Allmaras, 1991; Buman et al., 1994; Nicoullaud et al., 1994; Pellerin and Pages, 1996; Costa et al., 2002). Table 2.9 shows a few studies conducted in different countries with their reported results. Despite such vast literature there have been always some limitations in root system measurements. The purpose of this brief review is therefore not to give a comprehensive description of

techniques for studying root systems, but rather to review two techniques from above literature review found to be suitable for use in the present study.

2.7.1 Profile wall technique

Bohm (1976) used this technique to measure maize crop root systems in USA. A trench 150 cm long and 150 cm wide was excavated across the plant rows and a layer of soil was removed from the surface of the trench to expose a soil profile from which records of the partially exposed roots was made. A nearly 5 mm layer of soil was washed from the entire profile wall with a fine sprayer pump. Immediately after spraying a metal frame (interior 100 x 100 cm) with grids (5 x 5 cm) was laid against the profile wall and the length of roots exposed were estimated by counting the numbers of 5 mm lengths of root in each grid area. Root lengths were estimated at 50, 66 and 88 days after planting in one trench. The first profile was smoothed at a distance of 5-10 cm from the base of a maize plant. The second and third profiles were made in the same trench but at 20-30 cm beyond the previous profile. This technique provided an estimation of the root length in a soil volume.

Table 2.9 Techniques used in field/laboratory experiments to estimate size of maize root system and reported results.

Country & Source	Techniques used	Measured Indicators & results
USA Bohm (1976)	Trench Profile wall	Total root length (m/m^2) at 66 days was 1190 at 0-1 m depth.
UK Reid (1981)	Soil-glass interface	Mean root lengths of maize root hairs 0.90 mm at 7 DAS.
USA Anderson (1988)	Soil cores (whole & spatially weighed)	Root length 2034 m/plant & root weight 46 g/plant at 15 weeks from planting.
USA Kuchenbuch and Barber (1988)	Soil cores	Root length density (km/m^2) of 5.12 (1976) to 12.84 (1982) at 12 weeks from planting.
USA Buman et al. (1994)	Profile wall & monolith mapping	Root length density 0.5 cm /cm^3 at V6 development stage.
Canada Costa et al. (2002)	Image analysis	Total root length 4 km and root surface area 3.2 m^{-2} at silking.

This technique has the main advantage of being suitable for various soil types and instant measurement but is however, labour intensive, time consuming and, as with total excavation, causes extensive soil disturbance (for more detail see Chapter 5, section 5.4.1). It can also be difficult to obtain a statistically meaningfull numbers of replicates although data from this type of study can be combined with those from root observation studies to give total root system values (Atkinson, 1983).

2.7.2 Soil coring technique

Soil coring is probably the most frequently used technique of root sampling. Cores can be taken with a range of techniques from simple hand-held augers to power-driven systems. It is not generally suited to stony soils but would suit the silt loam texture commonly used for maize and sweet corn in New Zealand. Anderson (1988) used this technique successfully to measure maize crop root systems in USA. Soil cores were taken using a 7.6 cm diameter steel tube, directly over the plant, at mid row (38 cm from the row) and halfway between these two samples (19 cm). The cores were taken to 60 cm deep and divided into 6 sections (0-7, 7-14, 14-21, 21-28, 28-44 and 44-60 cm). No soil compression was observed when the cores were taken due to the large diameter of the tube. The soil sections were agitated in water on a 1 x1 mm screen to separate roots from soil. Roots in the top 60 cm of soil accounted for 87% of the total root mass in samples taken up to 1.2 m deep after grain harvest. A modification of this technique which uses pressurized water spray jets and air flotation has been described by Smucker et al. (1982) as the "hydro-pneumatic elutriation system". With this technique, roots as small as 0.125 mm diameter were recovered. The root samples were frozen until fresh root length, diameter, fresh weight and dry weight were measured. Root lengths were determined using a grid after removing all non-root organic material (Marsh, 1971; Newman, 1966; Tennant, 1975).

This technique works well under most conditions. However, estimates are sensitive to sample size and some care is needed in stony soils (for more detail see Chapter 5, section 5.4.1). In an experiment to assess nutrient cycling in grass and clover plots, root samples were collected with coring system, washed with the hydro-pneumatic elutriation method and root length determined using a comair root length scanner

successfully detected differences due to available soil phosphorus (Dawson-Mackie and Atkinson, 1991).

2.7.3 Need for technique development

Based on the existing information on techniques for studying root system, it was decided that first experiment in this study would incorporate an evaluation and comparison of profile wall and soil coring techniques to measure maize and sweet corn root system in the field.

2.8 Conclusions

There are contrasting P fertiliser recommendations for growing maize and sweet corn in NZ, although both are cultivars of the same species. Currently, the recommendations for soil P status at planting are much higher for sweet corn than maize. Limited experimental information is available to support these differences in recommendations.

Maize and sweet corn are the same species, and for this reason may be expected to have similar P requirement. On the other hand, the sweet corn crop is a shorter growing period crop compared with maize and therefore, might be expected to have lower P requirement. Against this, the rooting volume of sweet corn may be smaller than maize, which may provide it with reduced access to soil P reserves, making it more reliant on higher soil P status. Another explanation of the higher P requirement for sweet corn is the possibility that sweet corn absorbs and takes as much P as maize but it is less physiologically efficient in using P for biomass production. Despite such differences, many of the current agronomic practices for sweet corn are based on maize research and in most cases the appropriateness of these practices has not been challenged.

In maize and sweet corn cropping systems, P deficiency can have a negative effect on leaf area index (LAI). Therefore, the amount of photosynthetically active radiation (PAR) absorbed by the canopy and plant growth can be reduced, especially early in growth. Therefore, research studies to provide information on differences in the response of maize and sweet corn to soil P status must examine biomass yields at all stages of growth and not just final cob or grain yields.

Thus the evidence supporting different P fertiliser recommendations for maize and sweet corn is not strong. There are some contradicting aspects of the published information. These can be addressed on an experimental basis only by direct comparisons of maize and sweet corn in the field using different P application rates. Further, the previous studies conducted in New Zealand with maize and sweet corn were limited to the above ground plant characteristics/yields. No study has investigated or looked into the differences between maize and sweet corn root systems, which are critical determinants involved in P uptake as P uptake is dependent upon root systems and mycorrhiza infection in low P soils. There is no published comparison of the P efficiency of maize and sweet corn, yet differences in this could have a big influence on the comparative fertiliser requirements of these crops.

2.9 Study hypotheses

The overall aim of this study was to investigate P uptake characteristics for maize and sweet corn, with a major emphasis on the above and below ground plant characteristics response to P fertiliser. This was achieved by developing and testing the following hypotheses.

- Maize and sweet corn differ in the responsiveness to P fertiliser (maize requires less P than sweet corn to grow).
- Maize and sweet corn differ in plant P uptake and P use efficiency.
- Maize and sweet corn differ in the root systems (root biomass and distribution).

CHAPTER 3

MAIZE AND SWEET CORN GROWTH AND YIELD RESPONSES TO FERTILISER P IN THE HAWKE'S BAY & MANAWATU

3.1 Introduction

Chapter 1 and 2 highlighted the contrasting P fertiliser recommendations for growing maize and sweet corn under NZ arable cropping system, even though they are cultivars of the same species. Briefly, the previous research work on growing maize, suggests that if Olsen P test value is <11 mg P/kg then a pre-plant P fertiliser application of 50 kg P/ha followed by 20-35 kg P/ha as starter fertiliser, but if Olsen P value is >11 mg P/kg then 20 kg P/ha starter fertiliser is applied (Steele, 1985). Recently, Reid et al. (2001a), however recommended that if Olsen P test value is >10 mg P/kg, then no P fertiliser is needed, but if Olsen P value is less than 10 mg P/kg then 20-35 kg P/ha should be applied to maize as starter P fertiliser. In contrast, for growing sweet corn, the previous and recent recommendations are that optimum/target Olsen P test values should range from 28 to 35 mg P/kg (Clark et al., 1986; Prasad et al., 1988; Reid et al., 2001b) and if Olsen P test value is less than 26 mg P/kg then 35 kg P/ha is recommended to be applied as a starter P fertiliser (Reid et al., 2001b).

Currently, these contrasting recommendations are used to support decisions on P fertiliser application rates for growing maize and sweet corn in New Zealand. However, there has been no direct comparison of the P responsiveness of maize and sweet corn. The objective of this Chapter is to test the hypothesis that maize and sweet corn growth and yield differ in their responsiveness to fertiliser P (maize requires less P than sweet corn to grow under normal cropping practices). To test the hypothesis, two field experiments were designed and implemented to grow maize and sweet corn under contrasting environmental conditions. One field experiment was conducted in the Hawke's Bay and the second field experiment in the Manawatu.

3.2 Materials and Methods

3.2.1 Site descriptions of two field experiments

During the season 2001-02, the first field experiment was located within a conventionally cultivated maize paddock on the Longlands Road/Maraekakaho Road intersection about 5 km North East of Hastings in Heretaunga Plains, Hawke's Bay (Hawke's Bay Regional Council, Map/Plan No. 2683). The map reference of this location is at latitude 39^0 39'S and longitude 176^0 47'E. The Olsen P test value for topsoil (0-150 mm) of the site was 13 mg P/kg and other soil chemical properties before planting are in Table 3.1. The soil has been classified as a Te Awa silt loam (Weathered Orthic Recent Soil) with parent material of sandstone alluvium from greywacke overlying Taupo pumice alluvium (Hewitt, 1998); a detailed description of the soil physical properties of this site can be found in Griffiths (2001). The site has good natural drainage with moderate to slow infiltration and permeability rate. This site was selected due to its low Olsen P levels in order to observe the P responses to maize and sweet corn yields and root biomass.

During the season 2002-03, the second field experiment was located at the 'Frewens Block' near the Turitea stream at Massey University, Palmerston North campus. The map reference of this location is at latitude 40^0 23'S and longitude 175^0 37'E and the elevation is 40 m above mean sea level. The Olsen P test value for the topsoil layer (0-150 mm) was 11 mg P/kg. Other soil chemical properties before planting are in Table 3.2. The soil at this site is Manawatu fine sandy loam (Plate 3.1), classified as a Weathered Fluvial Recent Soil (Hewitt, 1998). The site has good natural drainage with moderate to good infiltration and permeability rate without any irrigation system. The site had previously been in ryegrass and white clover pasture, under sheep grazing and without any fertiliser applications for many years. Again, this site was selected due to its low Olsen P status to examine P responses of maize and sweet corn yields and root biomass.

Table 3.1 Soil chemical properties (0-150 mm soil depth) before planting in the Hawke's Bay experiment (season 2001-02).

Nutrient	Maize	Sweet corn
pH	6.3	6.3
Olsen P (mg P/kg)	13	12
S (mg S/L)	-	-
K*	5	5
Ca*	20	19
Mg*	77	72
Na*	43	39
CEC (me/100 g)	28	26
Mineralisable N (kg/ha)	49	53
Soil wt/volume (g/ml)	0.79	0.80
P retention (%)	20%	20%

Soil analysis conducted by Analytical Research Laboratory (ARL) in Napier. * MAF Quick test values
Mineralisable N (Keeney and Bremner, 1966) & Olsen P (Olsen et al., 1954) methods.
Values under cultivars are means of 9 observations

Table 3.2 Soil chemical properties (0-150 mm soil depth) before planting in the Manawatu experiment (season 2002-03).

Nutrient	Massey University Frewen's block site
pH	5.4
Olsen P (mg P/kg)	11
S (mg S/L)	5
K*	8
Ca*	9
Mg*	38
Na*	8
CEC (me/100 g)	18
Mineralisable N (kg/ha)	-
Soil wt/volume (g/ml)	1.04
P retention (%)	26%

Laboratory report, Fertiliser and Lime Research Centre, Massey University, Palmerston North
* MAF Quick test values

Factor for converting MAF soil Quick test units to me/100g for K, Ca, Mg and Na are 0.070, 0.955, 0.048 and 0.019, respectively (Cornforth and Sinclair, 1984). Note that these units are based on a constant bulk density of 0.91 g/m. Approximate values can be obtained by multiplying the conversion factor with MAF Quick test units.

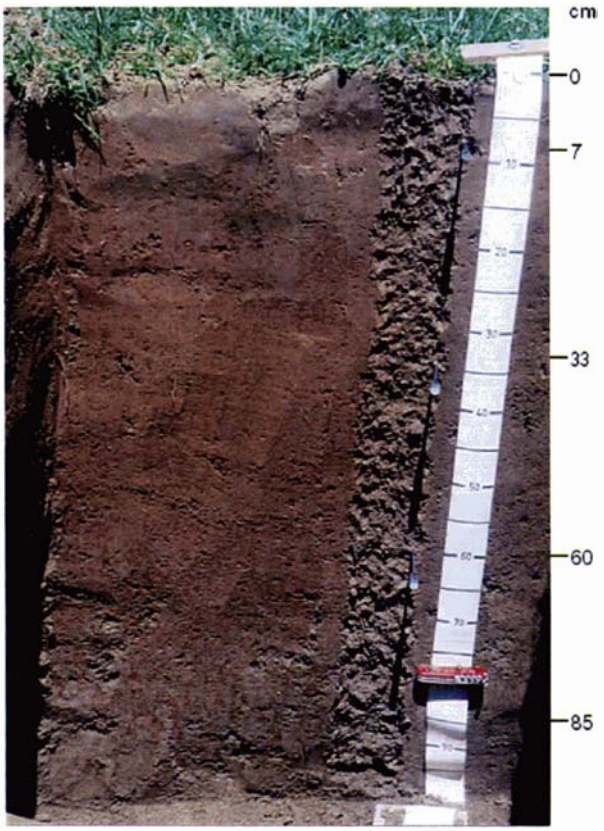


Plate 3.1 A profile of Manawatu fine sandy loam soil

3.2.2 Experimental design and treatments

The experimental design for the Hawke's Bay field experiment involved three P fertiliser treatments with maize (hybrid 34E79) and sweet corn (hybrid Challenger) arranged in a completely randomised design. Each plot was 9 m long and 5.3 m wide without any gap between plots. The three P fertiliser treatments were 0 (control i.e. no P fertiliser), 100 and 200 kg P/ha. Each treatment had three replicates.

The experimental design for the Manawatu field experiment involved seven P fertiliser treatments with maize (hybrid 36H36) and sweet corn (hybrid Challenger) arranged in a completely randomised design. Each plot was 4.5 m long and 5.3 m wide without any gap between the plots. Three P fertiliser treatments 0 (control i.e. no P fertiliser), 15 and 70 kg P/ha referred to as main P treatments, were replicated 5 times to provide data on dry matter yield, N and P uptake, root systems, plant height, soil water content and soil P status. The experiment also had four other P fertiliser treatments (7.5, 22.5, 30 and 50 kg P/ha) with 2 replicates to each treatment to extend the dry matter yield P response curve. Two P fertiliser treatments 7.5 kg P/ha (2 replicates per treatment) were also applied as a band placement of P fertiliser to observe the effect of P fertiliser by band placement on dry matter or root biomass.

3.2.3 Field operations (land preparation, fertiliser, sowing & thinning)

For the Hawke's Bay field experiment, the land was mouldboard ploughed with 20 cm ploughing depth adjustment in early November, 2001. A week after land preparation, 240 kg N/ha as urea and 75 kg K/ha as K_2SO_4 were applied to all plots and a power harrow was used to incorporate fertilisers and prepare the final seedbed. A day before planting, P fertiliser treatments (triple superphosphate having 21% P and 1% S) were broadcast manually on the plots followed by one pass of a power harrow. No herbicide or pesticide was applied. On 14 November 2001, all plots were hand-sown with two seeds per position at a depth of 2-3 cm. The selected configuration for maize was 76 cm between rows and 15 cm between plants within the rows to obtain a theoretical optimum plant population of 87719 plants/ha, whereas sweet corn seeds were planted 76 cm between rows and 18.5 cm between plants within the rows to have theoretical optimum plant population of 71124 plants/ha. Three weeks after sowing, the crop was

manually thinned to one plant per planting position and plants missing due to germination failure were replaced.

For the Manawatu field experiment, the field was first sprayed with glyphosate (360 gram/litre concentration)/ 3 L/ha on 15 September 2002 using a boom sprayer mounted on a tractor, to kill the existing weeds. On 6 October 2002, the complete block was ploughed using a 3 furrow mouldboard plough with 20 cm ploughing depth adjustment. One pass with a power harrow (Mashio) was used to obtain the rough seedbed preparation for fertiliser application and final seed bed preparation. A week after (14.10.2002) land preparation, lime was applied at rate of 1 tonne/ha on all the blocks. A preplant application of urea (50 kg N/ha) was applied to all plots. These two operations were carried out by using a fertiliser spreader mounted on a tractor. Fertiliser and lime were incorporated using a power harrow prior to sowing. A day before planting (21.10.2002), all plots were marked with pegs and tags and P fertiliser (triple superphosphate having 21% P and 1% S) was broadcast manually (Plate 3.2) as per treatment (except four plots left for band placement), followed by one pass of the power harrow for final seedbed preparation. Band placement of P at 7.5 kg P/ha was applied in four plots by a manual seeder fixed with inverted T opener after planting as shown in Plate 3.2. Second and third dressings of N fertiliser (urea) were applied at the rate of 50 kg N/ha to all plots by manual side dressing at 42 and 75 DAS (days after sowing) to avoid any nitrogen deficiency during the growth period.

The sowing was carried out on 22 October, 2002; late October sowing was recommended for the Manawatu region by Hardacre et al. (1991). Maize hybrid 36H36 and sweet corn hybrid Challenger were hand-sown with two seeds per position with configuration of 76 cm between rows and 18.5 cm between the seeds. Maize and sweet corn seedlings were manually thinned to one plant per planting position at 22 and 27 DAS, respectively to achieve a theoretical optimum plant population of 71124 plants/ha. At this stage plants missing due to germination failure were replaced. No herbicide and pesticide was applied after planting. However, California thistles that survived the glyphosate in a few places within some plots were removed by manually weeding from time to time.

Plate 3.2 P fertiliser broadcasting and band placement in field.

3.2.4 Weather observations

For the Hawke's Bay field experiment, the weather data such as air maximum and minimum temperature, solar radiation, rainfall and potential evapotranspiration during the crop growing season (from sowing to harvest) were obtained from Whakatu station, Hastings about 5 km away from the field experiment.

For the Manawatu field experiment, the weather data such as air maximum and minimum temperature, soil temperature, sunshine hours and rainfall during growing season were obtained from AgResearch Grassland CRI in Palmerston North, which is about 1 km from the experiment area.

3.2.5 Soil sampling and analyses

3.2.5.1 Soil texture and soil dry bulk density

Soil texture was determined on soil samples collected at 14 DAS from the Hawke's Bay field experiments. A quantitative assessment was made by manipulating a moistened soil samples rolling by hands, and relies on the different properties of sand, silt and clay. Sand has a gritty feel, silt has a smooth silky feel, and clay is sticky and adheres strongly to the fingers.

At the Hawke's Bay field experiment, the soil dry bulk density (BD) was measured at 37 DAS (21.12.2001) from 0-75, 75-150, 150-300 and 300-400 mm soil depths under the 100 and 200 kg P/ha treatments. In the Manawatu field experiment, the soil dry bulk density was measured at 45 DAS (5.12.2002) from 0-100, 100-200, 200-300 and 300-400 mm depth under maize and sweet corn control treatments and on 29 March 2003 from the excavated trench of maize and sweet corn control treatment plots (rooting depth plots) at 400-600, 600-800, 800-1000, 1000-1200 and 1200-1500 mm depths. Soil dry bulk density was determined as explained by McLaren and Cameron (1996) by using thin-walled cylindrical aluminium samplers, 50 mm in diameter and 50 mm in length that were pressed into the soil at the desired sampling depth. The samplers were withdrawn from the soil, carefully cleared weighted wet and then oven-dried at 105^0C overnight, and reweighed. Soil dry bulk density was calculated as the oven-dry mass of soil divided by the volume of the sample.

3.2.5.2 Soil water content

At the Hawke's Bay field experiment, the volumetric soil water content (θ_v) was measured by using TDR (Time Domain Reflectrometry) immediately after 2nd (67 DAS) and 3rd (102 DAS) root sampling stages. The TDR probes were pushed horizontally into the soil wall of root counting pits immediately below the plants (location L_1) and 30 cm away from the plants but within the row (location L_2). Four depths (0-100, 100-200, 200-300 and 300-400 mm) were used for both locations to determine θ_v from each replicate of P treatments under both cultivars.

At the Manawatu field experiment, the gravimetric soil water content (θ_g) was measured using a locally developed soil corer (Aslam's root corer) (Chapter 5, Plate 5.6) midway between the rows at 0-100, 100-200, 200-300 and 300-400 mm soil depths. These measurements were taken fortnightly from December 2002 to May 2003 from three replicates of each treatments in both cultivars. θ_g was calculated on dry weight basis by using the simple formula [(soil fresh weight - soil dry weight) ÷ by soil dry weight]. θ_g was further converted into volumetric θ_v basis by multiplying with the dry bulk density at each depth.

3.2.5.3 Soil chemical analysis (pre-plant and during crop growth)

At the Hawke's Bay field experiment, prior to planting in October 2001, soil samples (0-150 mm depth) were collected from each plot for chemical analysis for soil fertility status and selection of fertiliser application rate. The soil samples were sent to Analytical Research Laboratory (ARL), Napier for chemical analysis (results shown in Table 3.1). At 8 DAS (days after sowing) soil samples were also collected from each control plot of the maize and sweet corn treatments at 150-250, 280-320, 380-420, 580-620, 780-820 and 980-1002 mm to determine the soil P status (Olsen P) within a 1 m deep soil profile. During the remaining crop growth period, soil samples from two depths 0-150 and 150-300 mm were collected at each root sampling stages to determine soil P status (Olsen P) during the growth period. These fresh field moist samples were then air dried at room temperature and sieved through < 2 mm size sieve for soil P analysis as explained in section 3.2.5.4.

At the Manawatu field experiment, in September 2002 before planting, about 40 soil samples (0-150 mm depth) were collected over the whole block and pooled for soil chemical analysis. During crop growth, soil samples were collected from three soil depths (0-150, 150-300 and 300-400 mm) at 80 DAS (16.1.03) and 140 DAS (12.3.03) (first and third plant dry matter yield, nutrient uptake and root sampling stages) to measure Olsen P and soil mineral N (Nitrate and ammonium-N) at different crop growth intervals. Further, on 29 March, 2003 during trench excavation for root measurements, of maize and sweet corn control treatments, more soil samples were collected from the 400-600, 600-800, 800-1000, 1000-1200 and 1200-1500 mm depths for Olsen P and mineral N status. These fresh field moist samples were then air dried at room temperature and sieved through < 2 mm size sieve for soil P and soil N analysis as described in section 3.2.5.4 and 3.2.5.5.

3.2.5.4 Determination of sodium bicarbonate extractable phosphate (Olsen P)

Olsen P was determined using the method of Olsen et al. (1954). This method involved accurately weighing 1 g of air-dried soil (< 2 mm sieved) into a 50 ml polypropylene centrifuge tube, then adding 20 ml of 0.5 M $NaHCO_3$ solution. The soil samples and solution were shaken together for 30 minutes, in an end-over-end shaker, followed by centrifuging at 8000 rpm for one minute, and filtration through Whatman No.1 filter papers. Inorganic P was then determined by the phosphomolybdate method of Murphy and Riley (1962).

3.2.5.5 Determination of nitrate-N and ammonium-N in dry soil

The method used for analysing nitrate nitrogen (nitrate-N) as well as ammonium nitrogen (ammonium-N) involved accurately weighing 3 g of air dry soil into a centrifuge tube. Thirty mL of 2 M KCL solution was added to the soil sample and the centrifuge tube was then shaken in an end-over-end shaker for 1 hour. The sample was then centrifuged at 8000 rpm for 2-3 minutes, followed by filtration through Whatman No 41 filter paper. The amount of nitrate-N and ammonium-N in the extracts were measured using a Technicon II auto-analyser (Technicon, 1976; Downes, 1978).

3.2.6 Crop growth measurements

3.2.6.1 Plant dry matter yield

To measure the plant dry matter yield in the Hawke's Bay field experiment, three main harvests were carried out at 33 DAS (crop establishment stage), 75 DAS (vegetative stage) and 100 DAS (maturity stage). Plant dry matter yields were also measured when sweet corn fresh cob (115 DAS) and maize grain yields (180 DAS) were taken. In the Manawatu field experiment, six harvests were carried out at 50, 80, 110, 140, 170 and 200 DAS. At 50 DAS, when plant height for maize and sweet corn were 30 and 25 cm from ground, one full plant with roots attached was excavated gently using a spade from each replicate of the 0, 15 and 70 kg P/ha treatments, respectively. The shoot and root samples were separated and root (samples after washing) and shoot samples were dried to constant weight in the oven at 70^0 C to obtain plant and root dry weights. Harvests at 80, 110 and 140 DAS were taken from five replicates of 0, 15 and 70 kg P/ha treatments. At those days (80, 110 and 140 DAS), maize and sweet corn plants were also harvested from the 7.5, 22.5, 30 and 50 kg P/ha treatments.

In both the field experiments, at each harvest time, five plants from the mid section of a selected row of each plot were cut just above the brace root nodes. Each plant was divided into leaves, stem with tassel, and cob including husk and silks. The leaves were further divided into different age groups, cohort 1 (leaf 1-3), cohort 2 (leaf 4-6), cohort 3 (leaf 7-10) cohort 4 (leaf 11-14), cohort 5 (leaf 15-18) and cohort 6 (leaf 19-21). All samples were oven dried to a constant weight, separately at 70 ^{0}C to determine the final dry matter weight. Total plant dry weight (TDM) was measured by summing the leaves, stem and cob dry weights. Final results were expressed as dry weight per hectare.

3.2.6.2 Sweet corn fresh cob yield

At the Hawke's Bay field experiment, the sweet corn fresh cob yield (at 115 DAS) including wrapper leaves was determined with 76% seed moisture content. In the Manawatu field experiment, the sweet corn fresh cob (including wrapper leaves) yield was determined at 140 DAS with 72% seed moisture content. In both the experiments, the primary and secondary cobs from five plants per row were harvested and fresh weight was recorded to express the results as fresh cob yield per hectare. Seed moisture

content (%) was calculated on fresh weight basis by using a simple formula given below.

Seed Moisture = [(Seed fresh weight - Seed dry weight) ÷ Seed fresh weight] × 100

3.2.6.3 Maize grain yield

In the Hawke's Bay and Manawatu field experiments, the maize grain yields were determined at 180 and 200 DAS. Primary and secondary cobs from five plants per row were harvested and dried in an oven at 70^0C until constant dry weights were recorded. The grains were removed by hand from the dry cobs and weighed. Results are expressed as final grain yield (14% seed moisture content) per hectare.

3.2.6.4 Root growth measurements

Details of root sampling dates and measurements techniques are presented in Chapter 5, section 5.2.

3.2.7 Statistical analyses

Statistical analyses were performed by using the General Linear Model (GLM) software of the Statistical Analysis System (SAS Institute, 1999-2001). Data were analysed by Analysis of Variance (ANOVA) for a 2 x 3 factorial arrangement. Least significant differences (LSD) at 5% were used to detect differences (among means) between cultivars and P fertiliser treatments at different sampling stages.

3.3 Results

3.3.1 Hawke's Bay field experiment season 2001-02

3.3.1.1 Growing degree days and climatic conditions

Growing degree days is an index used to express crop maturity and is computed by subtracting a base temperature of 8^0C (recommended for maize in NZ) from the average of the maximum and minimum temperatures for the day i.e. (Tmax + Tmin)/2 - 8^0C. From planting to harvest, the maize and sweet corn accumulated 1411 and 1068 growing degree days (GDD; base 8^0C; Brooking and McPherson, 1989) as shown in Figure 3.1.

Total monthly solar radiation increased with air temperature from November 2001 onward with a maximum in January (717 MJ/m^2) and then decreased during February/March, 2002 with a minimum in April, 2002 (314 MJ/m^2) (Table 3.3).

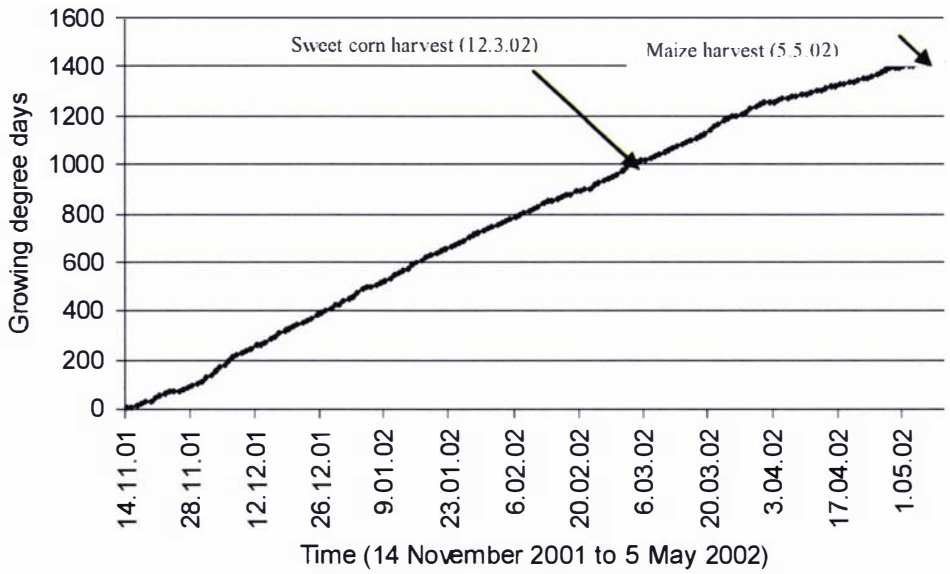


Figure 3.1 Distribution of growing degree days for maize (hybrid 34E79) and sweet corn (hybrid Challenger) in the Hawke's Bay experiment during the season 2001-02.

To reach maturity, maize crops generally require a minimum 375 mm of plant available water (Arnon, 1975). In this experiment, the soil water storage to 1 meter after 14 days of sowing was estimated to be around 190 mm. The additional total monthly rainfall (Table 3.3) provided a further 499 mm for the crop growth (1 November, 2001 to 30 April, 2002). The sum of soil available water plus rainfall exceeded the total ET (618 mm) by 71 mm for the same time period. In general, the overall climatic condition indicates that the important factors rainfall, air temperature and solar radiation were adequate for maize and sweet corn production (Table 3.3).

Table 3.3 Summary of monthly climatic data obtained from Whakatu station, Hastings.

Months (2001-02)	Air Temperature (0 °C) Maximum	Minimum	Solar Radiation (MJ/m²)/month	Rainfall (mm/month)	Potential ET (mm/month)
Nov, 01	19.8 (20.7)	10.2 (8.4)	578	28 (46)	110
Dec, 01	23.6 (22.2)	14.4 (10.7)	653	143 (69)	129
Jan, 02	23.5 (23.9)	12.9 (12.0)	717	107 (50)	139
Feb, 02	20.0 (23.8)	10.2 (12.0)	491	130 (54)	94
Mar, 02	24.5 (22.2)	11.1 (10.3)	489	43 (71)	93
April, 02	18.8 (19.6)	7.1 (7.2)	314	48 (69)	53

Solar radiation, rainfall & potential ET are sum of months and air temperatures are averaged of the months

Values in brackets (rainfall and air temperatures) are average for 30 years (1950-80) for Havelock North (NZ Meteorological Services, 1983)

3.3.1.2 Soil texture and dry bulk density

Measurements at 14 DAS, showed that the top two soil surface layers (150-250 and 280–320 mm) have approximately clay loam texture (35% clay, 35% sand and 30% silt), whereas the lower soil depths (380-1000 mm) have loamy sandy texture (70% sand, 10% silt and 10% clay) (Appendix 3.1). As explained in site description, this reflects the history of alluvium deposits and the contrasting parent materials of Hawke's Bay Heretaunga plains (Griffiths, 2001).

At 37 DAS, the soil dry bulk density of the top soil (0-300 mm) ranged from 0.76 to 1.02 g/cm^3, whereas at 400 mm soil depth ranged from 0.52 to 0.70 g/cm^3 (Appendix 3.2a) reflecting the change to coarser textures and pumice in the lower profile. Topsoil

dry bulk densities were uniform across the experiment sites and probably were not high enough to constrain root penetration (Scotter, 1996; McLaren and Cameron, 1996).

3.3.1.3 Soil water content

At 14 DAS, the gravimetric soil water content (θ_g) in the maize and sweet corn control treatments were not significantly different (P=0.05), indicating no differences in seedling water use for both cultivars. The θ_g was significantly lower in the top 320 mm of soil than in the lower pumice layers (Figure 3.2). Overall, θ_g followed the order 150-250 < 280-320 < 380-420 > 780-820 = 980 -1002 mm soil depths (P = 0.05). At this stage (14 DAS), around 140 mm of soil water was available in the root zone (0-400 mm) which was estimated by using soil dry bulk density values in top 0-400 mm soil depths.

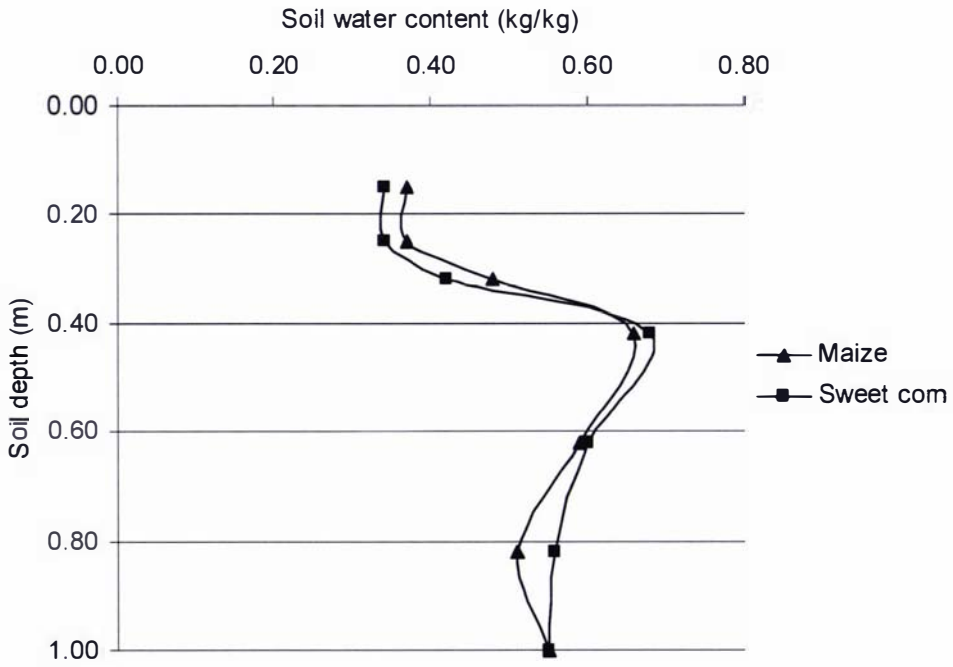


Figure 3.2 Soil water content depth distribution in the Hawke's Bay experiment at 14 DAS.

Table 3.4 shows the volumetric soil water content (θ_v) measured by TDR at 67 and 102 DAS (during 2nd and 3rd root sampling period). At 67 DAS, plant cultivars caused no significant differences in the θ_v, but the θ_v values at 0-400 mm soil depth was significantly lower under maize ($0.24 m^3/m^3$) than sweet corn ($0.26 m^3/m^3$) at 102 DAS, respectively. This shows that maize absorbed 8% more water from the top 400 mm of soil than sweet corn. P fertiliser application rate within or across cultivars had no effect on the θ_v at 102 DAS, however differences were found at 67 DAS. Soil depth caused largest variation in θ_v resulting from textural and bulk density changes and the frequency of rainfall. On average, the surface soil (0-100 mm) had lower θ_v compared to lower surface soil depths (100-200, 200-300 & 300-400 mm) throughout the sampling period.

Table 3.4 Soil water content (θ_v) under maize and sweet corn at 67 and 102 DAS taken by TDR method in the Hawke's Bay field experiment.

Treatments & Depths		Soil water content (θ_v) (m^3/m^3)							
		67 DAS (2nd root sampling)				102 DAS (3rd root sampling)			
P rate		Maize		Sweet corn		Maize		Sweet corn	
(kg/ha)	Depth (mm)	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2
0	0-100	.238	.203	.228	.188	.164	.169	.169	.210
	100-200	.277	.235	.305	.276	.267	.272	.267	.281
	200-300	.284	.273	.305	.284	.288	.323	.237	.235
	300-400	.275	.252	.252	.250	.282	.262	.307	.288
100	0-100	.210	.176	.206	.206	.164	.160	.183	.164
	100-200	.328	.288	.233	.259	.230	.267	.269	.274
	200-300	.284	.269	.291	.332	.257	.315	.300	.335
	300-400	.264	.237	.245	.260	.208	.213	.281	.274
200	0-100	.196	.154	.206	.211	.169	.162	.184	.208
	100-200	.235	.223	.269	.260	.240	.260	.247	.265
	200-300	.295	.316	.314	.269	.259	.293	.283	.288
	300-400	.153	.228	.215	.250	.250	.289	.264	.346
	Mean	0.25 a		0.26 a		0.24 a		0.26 b	
LSD (0.05)		0.012				0.013			
Significance									
cultivars		ns				s			
fertiliser		s				ns			
depth		s				s			
width		ns				ns			

values followed by same letters in mean row shows no significant differences ($P<0.05$)
Mean figures in rows (effect of cultivars) are average of 3 replicates & 3 treatments (72 observations);
L_1 and L_2 reflects the reading locations (L_1= vertical location below plant and L_2 = location at 30 cm in row)
LSD is for cultivars.

3.3.1.4 Soil Olsen P depth distribution and status

At 14 DAS, there were no significant differences in Olsen P test values between the maize and sweet corn control treatments at all depths. The top soil layers (0-150 mm) of control plots (0 kg P/ha) had higher Olsen P values (average 12 mg P/kg) compared to other subsurface layers (average 5 mg P/kg soil) (Figure 3.3). In this experiment, maximum depth covered was 1 m, as below which was pumice sandstone material.

Fertiliser treatments (100 and 200 kg P/ha) had a marked effect on Olsen P test values in the 0-150 mm soil depth (Table 3.5), but caused negligible change in Olsen P values at the 150-300 mm soil depth (Table 3.6). No significant differences in Olsen P test values (average for three treatments) between the cultivars were observed at any stage of crop growth at 0-150 and 150-300 mm soil depth (Table 3.5 and 3.6). In the maize control treatment, from 45 to 102 DAS, there was a decrease of 4 unit (14 to 10 mg P/kg soil) in Olsen P test values at the 0-150 mm soil depth. No such changes were apparent under sweet corn control treatment from 45 to 102 DAS. Overall, the results shows little change in Olsen P test values during crop growth.

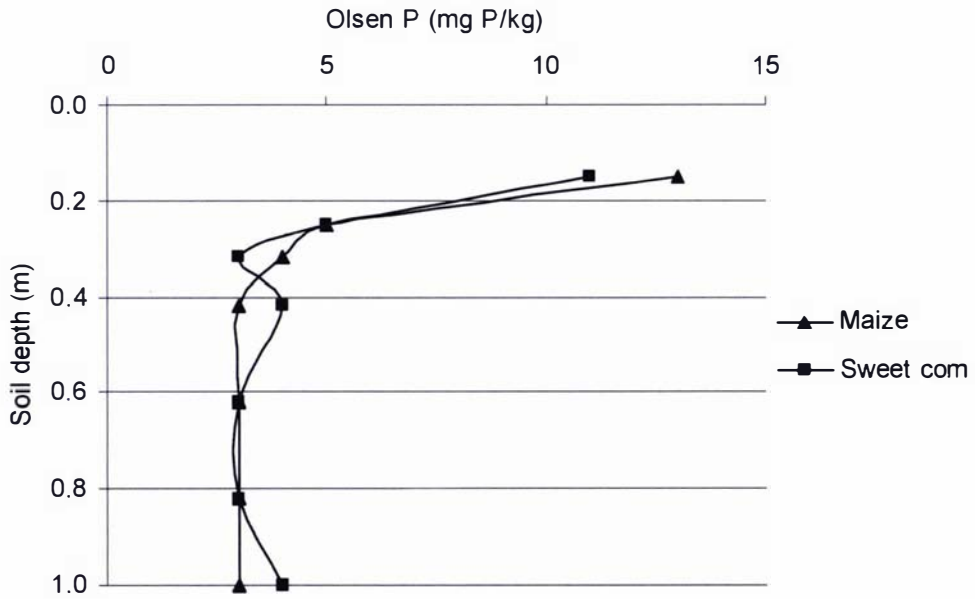


Figure 3.3 Olsen P depth distribution in the Hawke's Bay experiment (maize and sweet corn control treatments) at 14 DAS.

Table 3.5 Soil P status under maize and sweet corn during crop growth period at 0-150 mm soil depth in the Hawke's Bay field experiment.

Treatments P rate (kg/ha)	Olsen P (mg P/ kg soil)							
	45 DAS		67 DAS		102 DAS		132 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	14 a	13 a	16 a	13 a	10 a	12 a	8 a	13 a
100	20 a	17 a	30 b	40 b	18 b	25 b	18 b	18 a
200	42 b	29 b	33 b	41 b	27 c	27 b	30 c	36 c
Mean	25 a	20 a	27 a	31 a	18 a	21 a	19 a	22 a
LSD (0.05)	6.9		6.5		4.6		4.0	
Significance cultivar	ns		ns		ns		ns	
fertiliser	s		s		s		s	

Values followed by same letter in mean row (cultivars) and in columns(treatments) shows no significant differences (P< 0.05)
LSD is for cultivars

Table 3.6 Soil P status under maize and sweet corn during crop growth period at 150-300 mm soil depth in the Hawke's Bay field experiment.

Treatments P rate (kg/ha)	Olsen P (mg P/ kg soil)							
	45 DAS		67 DAS		102 DAS		132 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	7 a	7 a	7 a	6 a	6 a	6 a	4 a	3 a
100	7 a	8 a	8 a	8 a	6 a	5 a	6 a	5 a
200	13 b	9 a	6 a	8 a	6 a	4 a	6 a	8 b
Mean	9 a	8 a	7 a	7 a	6 a	5 a	5 a	5 a
LSD (0.05)	2.3		1.5		1.4		1.3	
Significance cultivar	ns		ns		ns		ns	
fertiliser	s		ns		ns		s	

Values followed by same letter in mean row (cultivars) and in columns(treatments) shows no significant differences (P<0.05)
LSD is for cultivars

3.3.1.5 Maize and sweet corn dry matter yields

Maize total dry matter yields were significantly (P=0.05) 64, 23 and 40% greater than sweet corn yields at 33, 75 and 100 DAS, respectively (Table 3.7). However, fertiliser P treatments caused no significant differences (P=0.05) in the total dry matter yield of either cultivar.

Figures 3.4 and 3.5 reports the partitioning of above ground dry matter yield for the maize and sweet corn crops at vegetative and reproduction stages during that season. Stem represented the largest dry matter component with both cultivars. At 75 DAS, sweet corn had approximately 1 t/ha of cob dry weight with no cob development with maize. At 100 DAS, there were no differences in cob with husk dry weights for both cultivars. Appendix 3.3 (a & b) shows the detailed plant dry matter partitioning with statistical analyses for maize and sweet corn dry matter yield during that season.

Table 3.7 Maize and sweet corn total plant above ground dry matter yields at 33, 75 and 100 DAS in the Hawke's Bay experiment during 2001-02 season.

Treatment P rate (kg/ha)	Total dry matter yield (t/ha)					
	33 DAS		75 DAS		100 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	0.18 a	0.10 a	10.6 a	8.9 a	20.1 a	13.9 a
100	0.19 a	0.11 a	12.4 a	9.3 a	20.6 a	13.5 a
200	0.18 a	0.11 a	10.8 a	9.3 a	22.2 a	16.6 a
Mean	0.18 a	0.11b	11.3 a	9.2 b	21a	15 b
LSD (0.05)	0.04		1.2		2.5	
Significance cultivar fertiliser	 s ns		 s ns		 s ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

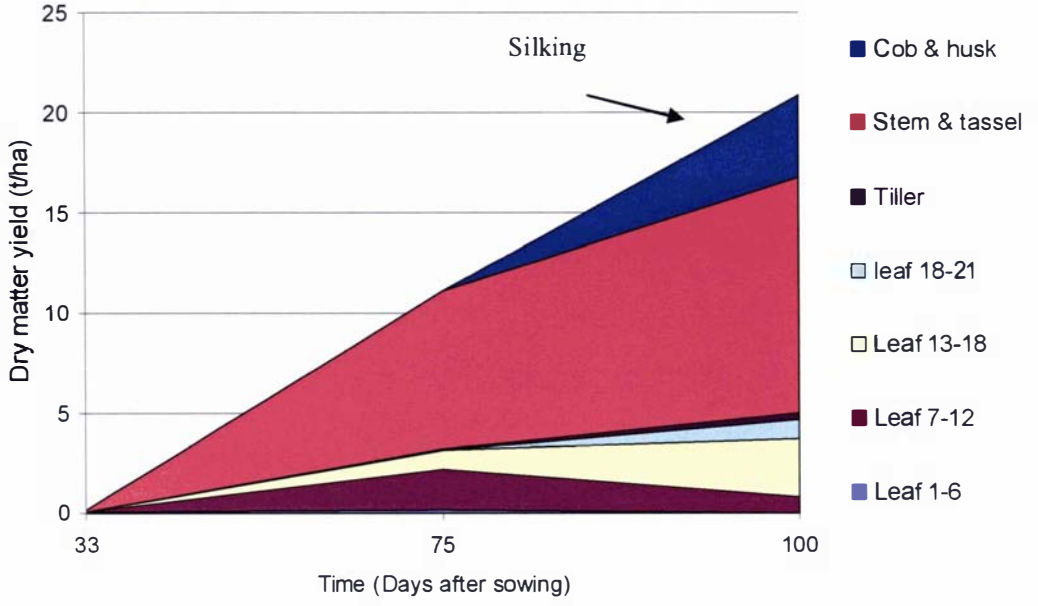


Figure 3.4 Maize (hybrid 34E79) plant partitioning dry matter yield (t/ha) at 33, 75 and 100 DAS in the Hawke's Bay (season 2001-02) . Results are presented as the means of the 3 P treatments.

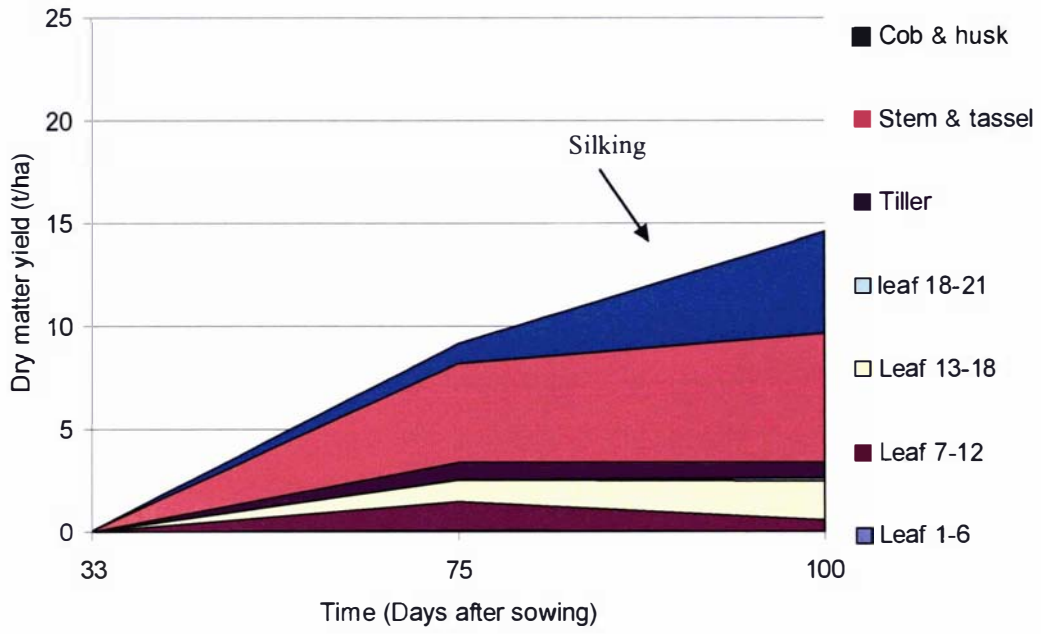


Figure 3.5 Sweet corn (hybrid Challenger) plant dry matter yield (t/ha) at 33, 75 and 100 DAS in the Hawke's Bay (season 2001-02). Results are presented as the means of the 3 P treatments.

3.3.1.6 Sweet corn fresh cob yield

At 115 DAS, the sweet corn fresh cob with wrapper leaves yields were 26.0, 27.2 and 26.7 t/ha under 0, 100 and 200 kg P/ha treatments, respectively (Table 3.8). There were no significant differences in fresh cob and total dry matter yield (TDM) at 115 DAS between the P fertiliser treatments. Overall, mean sweet corn fresh cob yield of 27 t/ha with 14 t/ha of dry matter yield were achieved with the plant population of 71124 plants/ ha.

3.3.1.7 Maize grain and total dry matter yields and harvest index

At 182 DAS (final harvest), the maize grain yields (14 % seed moisture content) were 15.5, 16.1 and 17.0 t/ha under 0, 100 and 200 kg P/ha treatments, respectively (Table 3.8). The maize total dry matter yields (at 182 DAS) were 29.0, 30.3, 31.3 t/ha under 0, 100 and 200 kg P/ha treatments (Table 3.8). The harvest index (mean for 3 P treatments) for maize was 0.46 (raw data at Appendix 3.5a). Overall, the mean maize grain yield of 16 t/ha and a total dry matter yield of 30 t/ha was achieved with a plant population of 87719 plants/ha during that season. There was no statistically significant influence of additional P fertiliser on either maize grain or total plant dry matter yields.

3.3.1.8 Application of " Maize and Sweet corn Calculators"

Measured sweet corn fresh cob and maize total dry matter yields were compared to potential yields predicted by "The Maize and Sweet corn Calculators'' software (Decision Support Software Programmes, NZ Institute for Crop and Food Research Ltd) (Reid et al., 1999b; Reid et al., 2002). The sweet corn calculator predicted 28.5 t/ha of fresh cob yield for that season (2001-02), which was within the coefficient of variation of the measured fresh cob yield at 26.6 t/ha. In contrast, the maize calculator predicted maize grain yield of 13 t/ha, which was below the measured yield of 16 t/ha at 14% grain moisture content. Further, the maize calculator under estimated the maize total dry matter yield at 100 and 175 DAS by more than the coefficient of variation of the measured yields (Figure 3.6). The Calculators predicted potential yield on basis of climatic conditions and available soil nitrogen contents.

Table 3.8 Effect of P fertiliser on sweet corn fresh cob and maize grain yields in the Hawke's Bay field experiment (season 2001-02).

Treatments (kg P/ha)	Sweet corn yield (115 DAS)		Maize yield (182 DAS)	
	Fresh cob (t/ha)	TDM (t/ha)	Grain (t/ha)	TDM (t/ha)
0	26.0 a	13.3 a	15.5 a	29.0 a
100	27.2 a	14.1 a	16.1 a	30.3 a
200	26.7 a	13.4 a	17.0 a	31.3 a
Mean	27	14	16	30
LSD (0.05)	2.9	1.5	2.2	3.2
Significance fertiliser	ns	ns	ns	ns

Mean values in columns (P treatments) followed by same letter show no significant differences (P=0.05)
LSD for P treatments. Sweet corn fresh cob and maize grain yields are at 76 and 14 % seed moisture content .

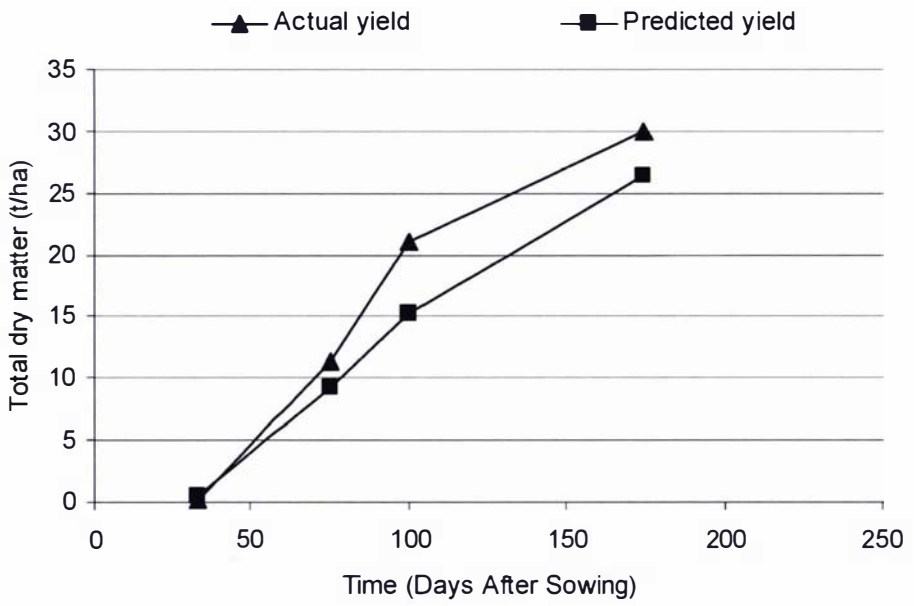


Figure 3.6 Predicted and measured dry matter yields of maize at 33, 75, 100 and 182 DAS in the Hawke's Bay experiment (2001-02).

3.3.2 Manawatu field experiment season 2002-03

3.3.1.1 Growing degree days and climatic conditions

From planting to harvest, the maize and sweet corn accumulated 1324 and 957 growing degree days in the Manawatu region during season 2002-03 (GDD; base 8^0C: Brooking and McPherson, 1989) (Figure 3.7). As usual, the total monthly solar radiation increased with air temperatures from November 2002 onward with a maximum in January (709 MJ/m^2) and then decreased during February to May 2003 with a minimum in June 2003 (Table 3.9). Total monthly ET increased with crop growth from November 2002 onward to March 2003 and then decreased during April/May 2003 (Table 3.9). More detail on climatic conditions for this experiment is discussed in Chapter 6.

The daily rainfall for October ranged from 0 to 17.2 mm/day with a total of 67.6 mm for the month (Table 3.9). The total rainfall from 1st to 21st October 2002 was 52.4 mm (before planting). On the sowing day (22nd October) around 1 mm of rain fell with a further 33.3 mm from sowing till seedling emergence. At planting, it was estimated that the soil volumetric water content of the top 75 mm of soil was 0.31 m^3/m^3 providing adequate water for seed germination and seedling emergence with approximately 162 mm of available water in the top 400 mm of the soil profile (for detail see Chapter 6 crop water use and nutrient uptake).

From emergence to maturity, a maize crop generally requires approximately 375 mm of plant available water (Arnon, 1975). The monthly rainfall for November and December 2002 were 42.4 and 84.4 mm, respectively. There was very little rain in January (19.8 mm), February (23.4 mm), March (26.8 mm) and April (31 mm) as compared to an average year. The total amount of rain received from planting till sweet corn harvest (23.10.02 to 15.3.03) was 202 mm, whereas till maize harvest (15.5.03) the figure was 264 mm, respectively. The rainfall data indicates that in the Manawatu 2002-03 soil water would not be recharged and crop growth may have suffered some water stress, however temperature and sunshine hours were normal for the crop vegetative and maturity growth.

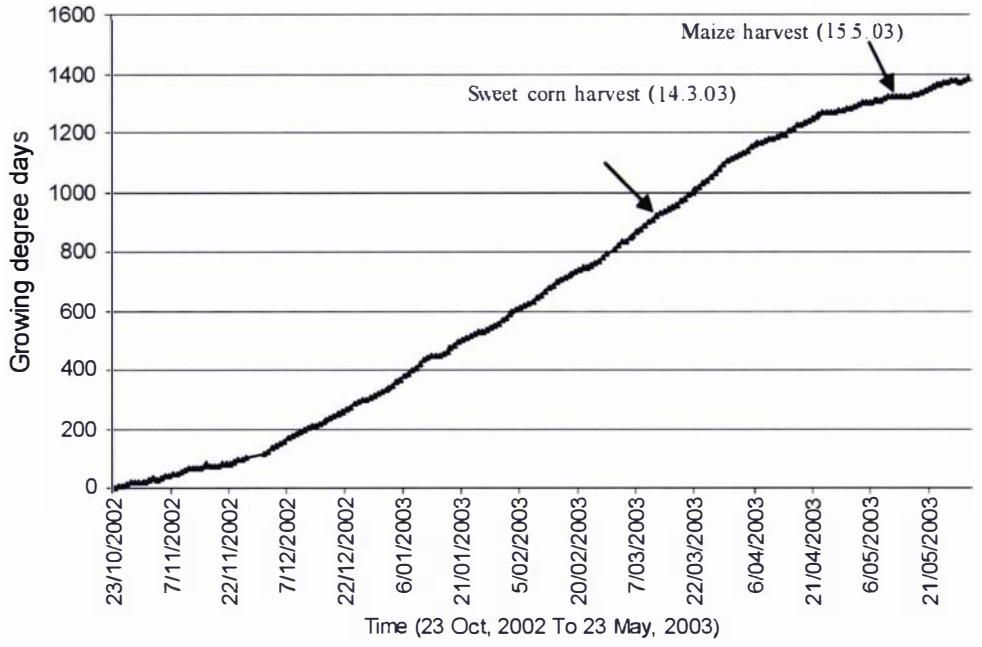


Figure 3.7 Distribution of growing degree days for maize (hybrid 36H36) and sweet corn (hybrid Challenger) in the Manawatu experiment during the season 2002-03.

Table 3.9 Climatic data (monthly averaged) for crop growth period for 2002-03 season recorded at AgriResearch Palmerston North at 9.00 AM daily.

Months (2002-03)	Air Temperature (°C)		Solar Radiation (MJ/m²)/month	Rainfall (mm/month)	Potential ET (mm/month)
	Maximum	Minimum			
October,02	14.3 (16.6)	5.2 (8.3)	22	68 (88)	78
November,02	15.5 (18.5)	6.7 (9.8)	531	42 (78)	81
December,02	19.5 (20.6)	10.7 (11.6)	683	84 (94)	117
January, 03	21.4 (21.9)	10.3 (12.3)	709	20 (79)	126
Feburary,03	22.4 (22.3)	10.1 (12.8)	615	23 (67)	109
March,03	24.4 (20.9)	12.2 (11.7)	585	27 (69)	101
April,03	18.8 (18.2)	8.4 (9.6)	317	31 (81)	47
May,03	16.8 (15.0)	6.1 (6.8)	229	107 (89)	26
June,03	15.2 (12.6)	7.0 (4.7)	145	187 (97)	-

Solar radiation and rainfall are monthly sums, and air and soil temperatures are average daily values.

Values in brackets (rainfall and air temperatures) are average for 52 years (1928-80) for Palmerston North (NZ Meteorological Services, 1983)

3.3.2.2 Soil water content

At 80, 110 and 140 DAS, the volumetric soil water contents (θ_v) in the root zone of maize was 12-15% lower (P=0.05) than that of sweet corn (Table 3.10). Greater soil water extraction by the maize crop can be attributed to two features; earlier canopy closure of the maize crop and deeper rooting depth (1.5 m) as measured on 29.3.03. The lowest θ_v of 0.12 m^3/m^3 was recorded in the 0-100 mm soil depth in late March, 2003 (27.3.03). At that stage the maize crop showed water stress symptoms. The rainfall of 38 mm between 27 March to 10 April, 2003 did increase soil water content but only in the 0-100 mm soil depth.

Phosphorus fertiliser application had no significant effect (P=0.05) on θ_v at any stage irrespective of cultivar. However, differences in θ_v were found for each soil depth. On average, the 100-200 mm soil depth θ_v remained high compared with other depths throughout sampling period, which was most probably due to the finer soil texture in this layer.

The θ_v values measured during crop growth period were further used in the FAO-56 soil water balance model to determine the water stress period for crop growth and its possible influence on nutrient (P & N) requirement and uptake by the two cultivars. More discussion of the interactions between maize and sweet corn water use and nutrient uptake during crop growth is presented in Chapter 6 [The soil dry bulk density for Manawatu experiment site for 0-100, 100-200, 200-300 and 300-400 mm soil depth is on Appendix 3.2b].

Table 3.10 Soil water content at different depths under maize and sweet corn in the Manawatu field experiment during the season 2002-03.

Treatments & depth		Soil water content (θ_v) (m^3/m^3)					
P rate (kg P /ha)	Soil Depth (mm)	80 DAS (16 Jan, 03)		110 DAS (14 Feb,03)		140 DAS (11 Mar, 03)	
		Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	0-100	0.24	0.26	0.17	0.20	0.17	0.20
	100-200	0.29	0.35	0.22	0.25	0.22	0.26
	200-300	0.25	0.31	0.20	0.23	0.21	0.24
	300-400	0.24	0.29	0.20	0.22	0.20	0.22
15	0-100	0.23	0.26	0.16	0.20	0.17	0.20
	100-200	0.28	0.33	0.22	0.25	0.22	0.22
	200-300	0.25	0.29	0.21	0.23	0.21	0.21
	300-400	0.23	0.26	0.20	0.20	0.19	0.20
70	0-100	0.23	0.27	0.16	0.21	0.15	0.19
	100-200	0.32	0.31	0.22	0.26	0.22	0.25
	200-300	0.29	0.29	0.21	0.24	0.20	0.23
	300-400	0.25	0.28	0.19	0.23	0.19	0.21
Mean	0-400	0.26 a	0.29 b	0.20 a	0.23 b	0.19 a	0.22 b
LSD (0.05)		0.012		0.010		0.010	
Significance							
cultivar		s		s		s	
fertiliser		ns		ns		ns	
depth		s		s		s	

Values followed by same letter in mean row (cultivars) show no significant differences (P=0.05).
LSD is for cultivars

3.3.2.3 Soil Olsen P depth distribution and status

In the Manawatu fine sandy loam soil, the Olsen P values decreased markedly with soil depth in maize and sweet corn control treatment plots (175 DAS measurement, Figure 3.8). The Olsen P values mean for two cultivars control treatment (14 mg P/kg soil) was greater in the top soil layers (0-150 mm) compared with all other subsurface layers up to 1.5 m depth (7 mg P/kg soil) (Figure 3.8).

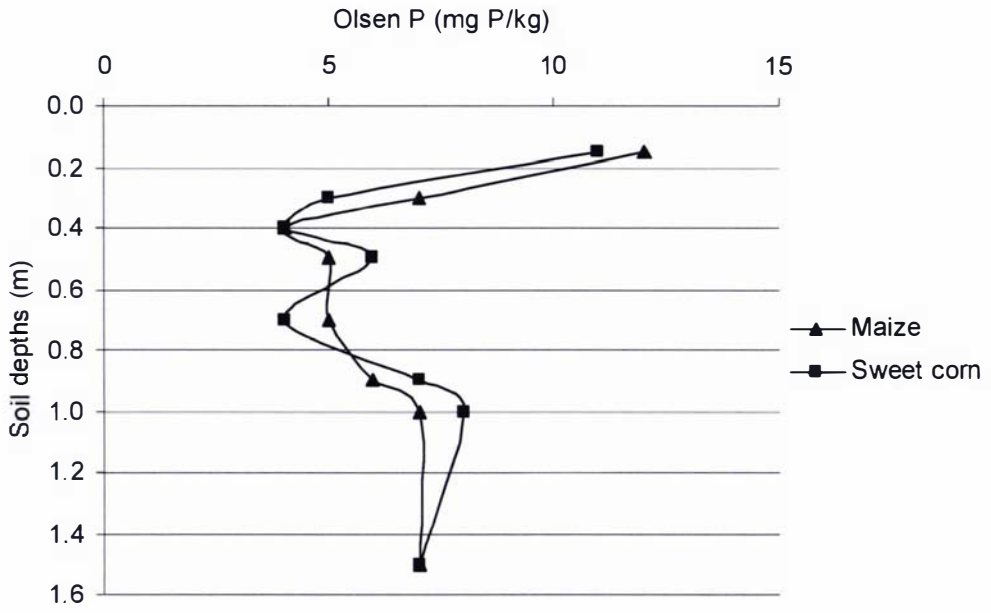


Figure 3.8 Olsen P depth distribution in the Manawatu experiment (maize and sweet corn control treatments) at 175 DAS.

The P fertiliser treatments (15 and 70 kg P/ha) significantly increased the Olsen P test values in the 0-150 mm and 150-300 mm soil depths at 80 DAS (Table 3.11). By 140 days these increased Olsen values were less evident with the 15 kg P/ha applied rate but remained for the 70 kg P/ha rate. With one exception, no significant differences in Olsen P values (mean for three P treatments) between the cultivars were noted at any stage of crop growth at 0-150, 150-300 and 300-400 mm soil depths (Table 3.11). At 140 DAS, the mean Olsen P value (0-150 mm depth) for the three P treatments was higher under maize (13 mg P/kg soil) than sweet corn (11 mg P/kg soil), a relative difference of 18 % (Table 3.11). Olsen P values did decline through the season. In the maize control treatment, from 80 to 140 DAS, the Olsen P test value decreased from 12

to 10 mg P/kg soil at 0-150 mm soil depth, from 9 to 6 mg P/kg soil at 150-300 mm soil depth and from 7 to 5 mg P/kg soil at 300-400 mm soil depth, respectively. In the sweet corn control treatment, between 80 and140 DAS, the Olsen P values decreased from 13 to 10 mg P/kg soil at 0-150 mm, 8 to 6 mg P/kg soil at 150-300 mm soil depth and 7 to 4 mg P/kg soil at 300-400 mm soil depth.

Table 3.11 Soil P status under maize and sweet corn during crop growth stages at 0-150, 150-300 and 300-400 mm depths in the Manawatu experiment.

Treat. P rate (kg/ha)	Olsen P (mg P/kg soil)											
	Soil depth 0-150 mm				Soil depth 150-300 mm				Soil depth 300-400 mm			
	80 DAS		140 DAS		80 DAS		140 DAS		80 DAS		140 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	12 a	13 a	10 a	10 a	9a	8 a	6 ac	6 a	7 a	7 a	5 a	4 a
15	14 ab	14 a	12 a	10 ab	9 ab	10 b	6 a	7 a	8 a	6 a	5 a	4 a
70	16 bc	15 a	17 b	12 bc	11 b	10 bc	8 bc	7 a	7 a	8 a	5 a	5 a
Mean	14 a	14 a	13 a	11 b	10 a	10 a	7 a	7 a	7 a	7 a	5 a	5 a
LSD (0.05)	1.6		1.6		1.2		1.2		1.0		1.1	
Significance												
cultivar	ns		s		ns		ns		ns		ns	
fertiliser	ns		s		ns		ns		ns		ns	

Values followed by same letter in mean row (cultivars) and in columns (treatments) shows no significant difference (P<0.05)
LSD is for cultivars

3.3.2.4 Soil mineral N content

At 80 DAS, the mean soil ammonium-N contents for both cultivars at 0-150 mm soil depth (20 kg N/ha) were substantially smaller than the soil nitrate-N contents (193 kg N/ha). A similar trend was found with other depths and time (140 DAS). Soil ammonium-N contents decreased with increasing depth irrespective of treatment but values were low, and the data has not been tabled.

Soil nitrate-N contents generally decreased with increasing soil depth, irrespective of P treatment, and there were still substantial quantities of soil nitrate-N (19-41 kg N/ha) in the 300-400 mm depth. The higher nitrate concentrations (171-207 kg N/ha) in the upper layers (Table 3.12) reflects both the addition of 150 kg N/ha at 0-150 mm layers at crop establishment and the fact that soil organic N concentrations are higher in the upper profile.

The cultivar type had a significant influence on soil nitrate-N concentrations in 0-150, 150-300 and 300-450 mm soil depths at 80 and 140 DAS (Table 3.12). The soil nitrate-N concentrations under sweet corn were greater than those under maize except for 300 to 400 mm depth at 80 DAS (Table 3.12). There was no significant P treatment effects on the nitrate-N content of the 0-150 mm soil depth during the two sampling period (80 & 140 DAS). Between 80 and 140 DAS (60 days) at 0-150 mm depth under both cultivars, the soil nitrate-N content remained unchanged. The reasons are discussed at length in Chapter 6.

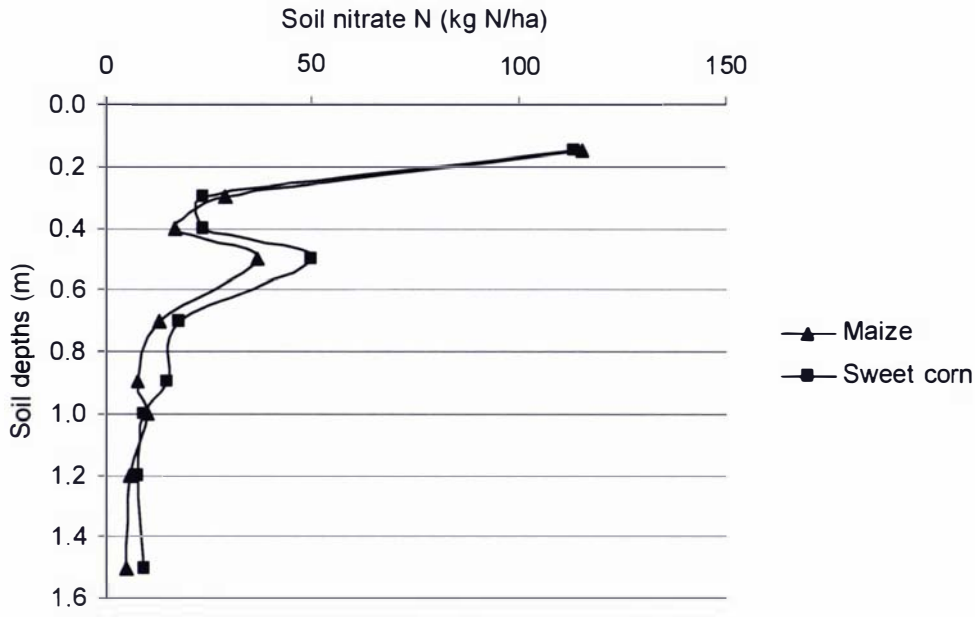


Figure 3.9 Soil nitrate-N depth distribution in the Manawatu experiment (maize and sweet corn control treatments) at 140 DAS.

Table 3.12 Soil nitrate-N contents under maize and sweet corn during crop growth stages at 0-150, 150-300 and 300-400 mm depths in the Manawatu experiment.

Treat. P rate (kg/ha)	Soil Nitrate-N (kg N/ ha)											
	Soil depth 0-150 mm				Soil depth 150-300 mm				Soil depth 300-400 mm			
	80 DAS		140 DAS		80 DAS		140 DAS		80 DAS		140 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	164	209	168	191	107	135	39	61	58	38	13	22
70	194	205	174	201	115	160	68	74	24	28	25	36
Mea	179 a	207 b	171 a	196 b	111 a	148 b	54 a	68 b	41 a	33 b	19 a	29 b
LSD (0.05)	22.4		20.4		30.2		14.2		8.5		8.7	
Significance cultivar	s		s		s		s		s		s	
fertiliser	ns		ns		ns		s		s		s	

Values followed by same letter in mean row (cultivars) shows no significant differences (P<0.05)
LSD is for cultivars

3.3.2.5 Maize and sweet corn dry matter yields

At 50 DAS, the maize plants were 6 cm taller and had produced 66 % more shoot dry weight than sweet corn plants (Table 3.13). Maize also had 3 cm longer fresh root length and had produced 1.7 times more root dry weight (Chapter 2, Plate 2.3). Due to the small size of the root samples, the root samples from each replicate were pooled together per treatment to obtain the dry weight. Therefore, statistical analysis on the root data was not possible. Differences in P fertiliser rate caused no differences in plant height, shoot dry weight and fresh root length at that initial crop establishment stage.

Table 3.13 Maize and sweet corn shoot and root characteristics at 50 DAS in the Manawatu experiment.

Treat.	Plant ht (cm)		shoot DM (kg/ha)		[2]Root length (cm)		[1]Root DM (kg/ha)		Ratio (RSR) (root:shoot)	
P rate (kg/ha)	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	32.2	25.4	72	37	22.0	18.2	25	10	0.35	0.27
15	32.6	26.2	73	45	21.1	17.8	27	11	0.37	0.24
70	33.0	27.0	74	49	21.9	19.8	28	10	0.37	0.20
Mean	32 a	26 b	73 a	44 b	22 a	19 b	27	10	0.36	0.24
LSD (0.05)	2.75		7.8		2.3					
Significance cultivar	s		s		s		-		-	
fertiliser	ns		ns		ns		-		-	

Mean values followed by same letter in row shows the effect of cultivars (P = 0.05).

[1] Root DM data from weight of bulked replicates, [2]Root length is maximum fresh root length

LSD is for cultivars

The total dry matter yields of maize were 118, 46 and 39% greater than sweet corn at 80, 110 and 140 DAS, respectively. These differences were significant at P=0.05 (Table 3.14). The rate of P fertiliser application in the main P treatments showed no significant effect on dry matter yield of either maize or sweet corn.

Figures 3.10 and 3.11 show the partitioning of shoot dry matter yields for maize and sweet corn at different crop growth stages. The results obtained in this field experiment follow the same trends observed in the Hawke's Bay field experiment but the yields for

the corresponding DAS were lower. Appendix 3.4 (a, b & c) shows the detailed plant partitioning with statistical analyses for maize and sweet corn dry matter yield at those sampling periods.

The other P fertiliser treatments (7.5, 22.5, 30 and 50 kg P/ha) produced no differences in dry matter yield with both cultivars at 80, 110 and 140 days after sowing, respectively (Figure 3.12 and 3.13).

Table 3.14 Maize and sweet corn total shoot dry matter yield at 80, 110 and 140 during 2002-03 season in the Manawatu experiment.

Treatments P rate (kg/ha)	Total shoot dry matter (t/ha)					
	80 DAS		110 DAS		140 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	2.98 a	1.22 a	8.9 a	5.5 a	15.2 a	10.5 a
15	2.54 a	1.22 a	8.3 a	5.7 a	15.8 a	10.7 a
70	2.66 a	1.36 a	8.6 a	6.5 a	14.9 a	11.7 a
Mean	2.72 a	1.25 b	8.6 a	5.9 b	15.2 a	10.9 b
LSD (0.05)	0.32		0.90		0.74	
Significance cultivars fertiliser	 s ns		 s ns		 s ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

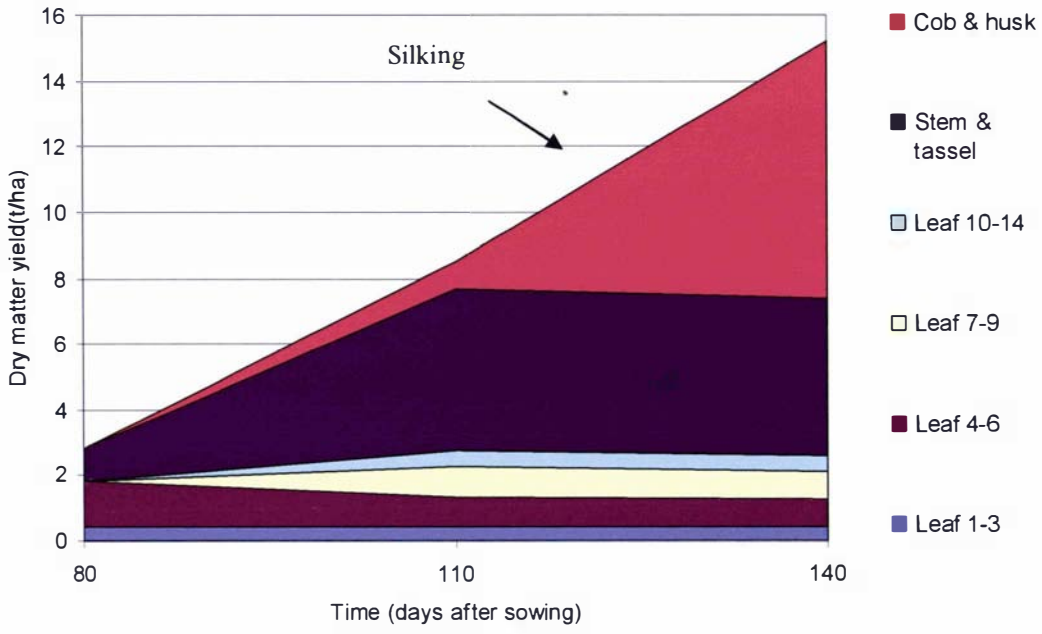


Figure 3.10 Maize (hybrid 36H36) plant partitioning dry matter yield (t/ha) at 80, 110 and 140 DAS in the Manawatu experiment. Results are presented as the mean of 3 P treatments.

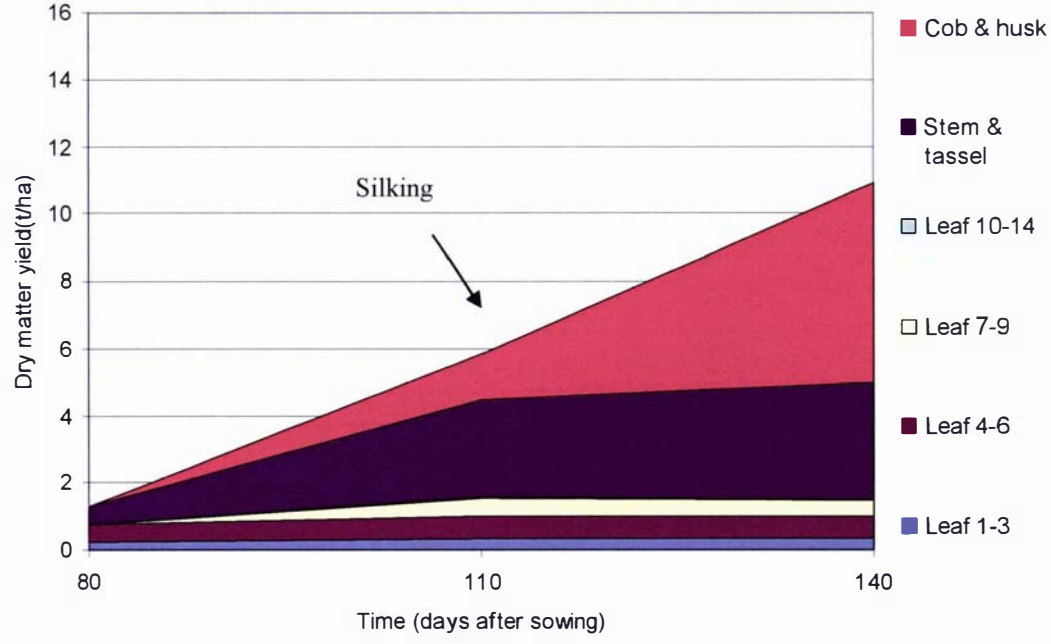


Figure 3.11 Sweet corn (hybrid Challenger) plant partitioning dry matter yield (t/ha) at 80, 110 and 140 DAS in the Manawatu experiment. Results are presented as the mean of 3 P treatments.

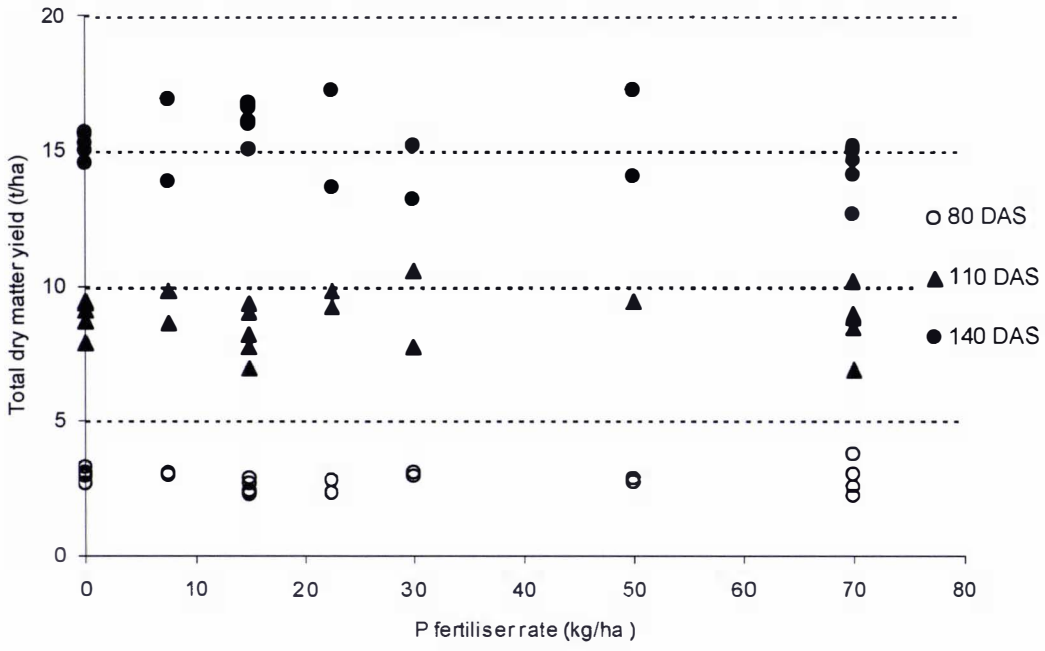


Figure 3.12 Effect of P fertiliser rate on maize (hybrid 36H36) plant dry matter yield (t/ha) (mean P treatments) at 80, 110 and 140 DAS during 2002-03 season in the Manawatu experiment.

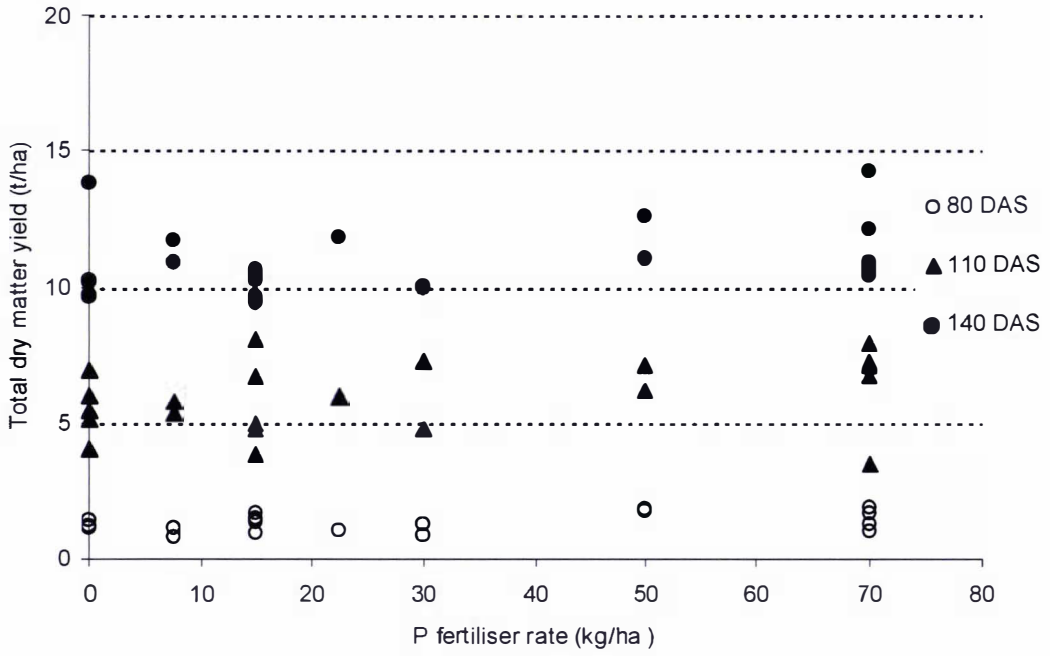


Figure 3.13 Effect of P fertiliser rate on sweet corn (hybrid Challenger) plant dry matter yield (t/ha) (mean P treatments) at 80, 110 and 140 DAS during 2002-03 season in the Manawatu experiment.

3.3.2.6 Sweet corn fresh cob yield

At 140 DAS, the sweet corn fresh cobs with wrapper leaves yields were 27.8, 27.8 and 28.4 t/ha under 0, 15 and 70 kg P/ha treatments, respectively (Table 3.15). The application of different P fertiliser rates had no significant effect (P=0.05) on the fresh cob and dry matter yields. Overall, an average of 28 t/ha fresh cob yield and 11 t/ha of total dry matter yield (115 DAS) were achieved during that season (2002-03) with the plant population of 71124 plants/ha.

3.3.2.7 Maize grain and total dry matter yields and harvest index

At 200 DAS (final harvest), the maize grain yields (14 % seed moisture content) were 9.2, 10.8 and 10.2, and total dry matter yields of 16.6, 19.7 and 18.2 under 0, 15 and 70 kg P/ha treatments, respectively (Table 3.15). The harvest index (mean of 3 P treatments) for maize was 0.47 (raw data at Appendix 3.5b). There was no significant effect of P fertiliser rate on either maize grain, or total dry matter yields. The mean yield of the three main P treatments shows that maize hybrid 36H36 produced a grain yield of 10 t/ha with 18 t/ha of dry matter yield with a plant population of 71124 plants/ha. Good commercial crops in the Manawatu are expected to yield 12 tons of grain in a season with adequate rainfall and growing degree days.

3.3.2.8 Maize and sweet corn height

There were highly significant differences (P<0.0001) between the plant height for both cultivars (Table 3.16) The result shows that maize was taller than sweet corn from emergence to crop maturity and final harvest. The differences were 3 cm at 40 DAS, but later the differences were more pronounced and around 50 cm. Maize attained the maximum height at 110 DAS, whereas sweet corn grew another 8 cm between 110 to 140 DAS. The results indicate that basically both cultivars attained peak height at tasselling stage, which was at 110 DAS.

No significant differences (P=0.05) were found between the P fertiliser treatments for both cultivars at any time.

Table 3.15 Effect of P fertiliser on sweet corn fresh cob and maize grain yields in the Manawatu experiment (season 2002-03).

Treatments (kg P/ha)	Sweet corn yield (140 DAS)		Maize yield (200 DAS)	
	Fresh cob (t/ha)	TDM (t/ha)	Grain (t/ha)	TDM (t/ha)
0	27.8 a	10.5 a	9.2 a	16.6 a
15	27.8 a	10.7 a	10.8 a	19.7 a
70	28.4 a	11.7 a	10.2 a	18.2 a
Mean	28	11	10	18
LSD (0.05)	3.8	0.78	1.9	3.2
Significance fertiliser	ns	ns	ns	ns

Mean values in columns (P treatments) followed by same letter show no significant differences (P=0.05)
LSD for P treatments. Sweet corn fresh cob and maize grain yields are at 76 and 14 % seed moisture content

Table 3.16 Effect of P fertiliser on plant height at different crop growth stages in the Manawatu experiment (season 2002-03).

Treatments	Plant height (cm)							
	40 DAS		80 DAS		110 DAS		140 DAS	
P rate (kg/ha)	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	16 a	13 a	144 a	91 a	211 a	148 a	209 a	158a
15	16 a	13 a	138 a	86 a	203 a	151 a	206 a	158a
70	17 a	14 a	139 a	92 a	207 a	154 a	204 a	159a
Mean	16 a	13 b	140 a	90 b	207 a	151 b	206 a	159 b
LSD (0.05)	0.93		5.92		6.9		4.7	
Significance cultivars	<.0001		<.0001		<.0001		<.0001	
fertiliser	ns		ns		ns		ns	

Means values in row (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

3.3.2.9 Application of "Maize and Sweet corn Calculators"

Measured sweet corn fresh cob and maize total dry matter yields were compared to yields predicted by Maize and Sweet corn calculators software (Decision Support Software Programmes, Crop & Food Research) (Reid et al., 1999b; Reid et al., 2002). The sweet corn calculator predicted 23.7 t/ha of fresh cob yield at 114 days after sowing for that season. However, the measured fresh cob yield was 28.1 t/ha at 140 DAS. This difference of 4.4 t/ha between predicted and measured yield could be due to the difference of 26 extra days when sweet corn was harvested in field. In contrast, the maize calculator significantly over estimated the maize total dry matter yield at 75, 100 and 175 DAS (Figure 3.14).

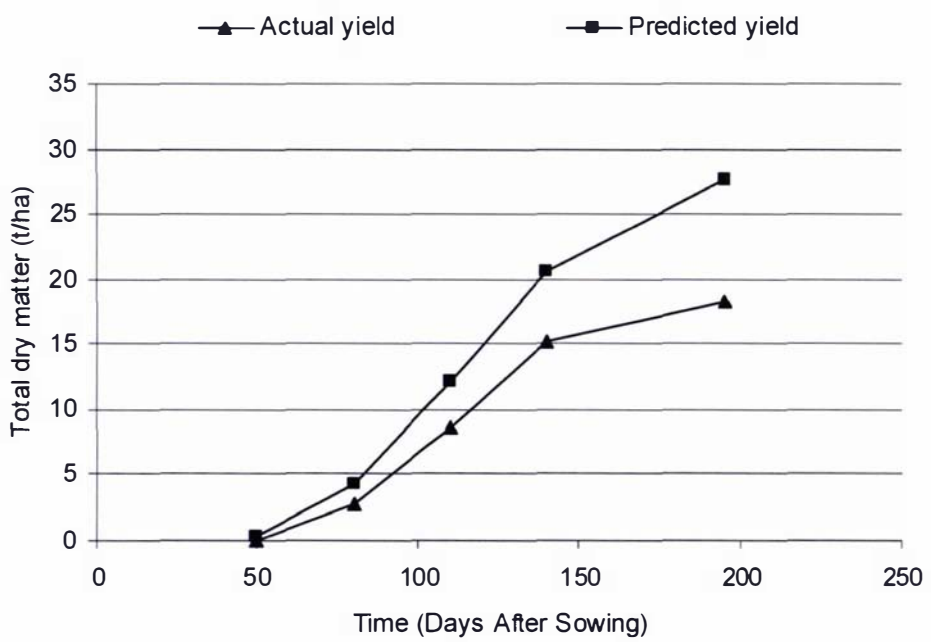


Figure 3.14 Predicted and measured dry matter yields of maize at 50, 80, 110, 140 and 200 DAS in the Manawatu experiment during 2001-02 season.

3.4 Discussion

3.4.1 Cultivars differences in total dry matter yield

Maize dry matter yields were higher than sweet corn dry matter yields in both the Hawke's Bay (43 % at 100 DAS) and the Manawatu (39 % at 140 DAS) field experiments throughout all sampling stages (Table 3.7 and 3.14). In both the field experiments, this difference was evident in both shoot and root dry matter (root biomass is discussed in Chapter 5, Table 5.2 and 5.3). Note that in the Hawke's Bay experiment, maize (87119 plants/ha) and sweet corn (71124 plants/ha) were sown with different plant populations, however, in the Manawatu experiment, both cultivars were planted with an identical plant population of 71124 plants/ha. Overall, the results from both field experiments suggests that the yield potentials of maize and sweet corn cultivars differ probably for genetic reasons rather than site specific or soil limitations. It is common for maize genotypes to differ in shoot, or root, characteristics. Several other studies have also reported differences in maize yield caused by genotype. For example, Burris (1977) showed significant differences in shoot and root dry weights between inbred lines. Kuchenbuch and Jung (1988) also reported genetically caused differences in maize shoot and root weights. Similarly, Baria-Szabo et al. (1990) also demonstrated that shoots of some inbred lines were significantly longer than the others.

3.4.2 Dry matter yield response to soil and fertiliser P

Phosphate fertiliser application caused no significant increases in maize and sweet corn dry matter yields either in the Hawke's Bay (2001-02), or the Manawatu (2002-03) field experiments ($P=0.05$). This does not support the hypothesis formed in Chapter 2, section 2.9 that maize and sweet corn differ in their responsiveness to fertiliser P (i.e. maize requires less fertiliser P than sweet corn to grow) .

The experimental sites, where these two experiments were conducted, had Olsen P test values of 13 mg P/kg (Hawke's Bay) and 11 mg P/kg (Manawatu) before planting. These Olsen values were near optimum for maize (10-15 mg P/kg soil) growth but far below the recommended values (26-35 mg P/kg soil) for sweet corn.

For maize, the previous research work suggests that if Olsen P is >11 mg P/kg, then 20 kg P/ha should be applied as starter fertiliser (Steele, 1985). In contrast, Reid et al. (2001a) recommended that if Olsen P test value is >10 mg P/kg, then no P fertiliser is needed for growing maize, but if Olsen P test value is less than 10 mg P/kg then 20-35 kg P/ha should be applied to maize as starter P fertiliser. The lack of maize yield response to fertiliser P in the Hawke's Bay and the Manawatu field experiments is consistent with the recommendations of Reid et al. (2001a) that if Olsen P test values are ≥ 10-13 mg P/kg, then no P fertiliser is needed for growing a maize grain crop in New Zealand.

In this study, the total dry matter yields (at final harvest) for maize (hybrid 34E79) were 30 t/ha in the Hawke's Bay (87719 plants/ha) and 18 t/ha (hybrid 36H36) in the Manawatu (71124 plants/ha) field experiments. Densley (2002) reported that the contract maize growers in North Island when cropping maize silage following annual ryegrass obtain total dry matter yields of 30 t/ha each year. Therefore, the dry matter yield of 30 t/ha obtained in the Hawke's Bay field experiment represents a good commercial yield. In contrast, the total dry matter yield of 18 t/ha in the Manawatu field experiment was lower than compared to the Hawke's Bay. The reason for this lower yield in the Manawatu experiment was because of a lower plant population of 16595 plants/ha, a different maize hybrid/cultivar and the dry summer season 2002-03 compared to the Hawke's Bay season 2001-02.

For growing sweet corn, the previous and current recommendations for target/optimum Olsen P test values range from 28 to 35 mg P/kg soil (Clark et al., 1986; Prasad et al., 1988; Reid et al., 2001b). If Olsen P test values are less than 26 mg P/kg then 35 kg P/ ha is recommended to be applied as a starter P fertiliser (Reid et al., 2001b). In both the field experiments, the Olsen P test values were far below the recommendations for growing sweet corn. Therefore, in both field experiments, sweet corn yield responses were expected with the P fertiliser treatments. But no such effect of P fertiliser on dry matter yield occurred. The lack of total dry matter yield response in both field experiments does not support the hypothesis that sweet corn requires higher soil P status than maize nor does it support the recommended target Olsen P test values (26-35 mg P/kg soil) for growing sweet corn in New Zealand. The next two sections discuss the

marketable yield of both crops, fresh cob yield for sweet corn and maize grain yields produced during those two seasons.

3.4.3 Sweet corn fresh cob yield and response to P fertiliser

The sweet corn yields of fresh cobs with wrapper leaves were 27 and 28 t/ha in the Hawke's Bay and the Manawatu field experiments, respectively, at a plant population of 71124 plants/ha (Table 3.8 and Table 3.15). These yields compare well to commercial crop and are within the limits or close to the yields reported by others (Brooking and McPherson, 1986; Reid et al., 2001b). Sweet corn yield can differ with type of cultivar, plant population and nitrogen availability (Hansen, 2000). Hanly (2001) reported a sweet corn harvestable ear yield of 20 t/ha (cultivar Punch) with 59000-65000 plant/ha in the Gisborne region. Similarly, Hansen (2000) also reported sweet corn (Jubilee and SS42) harvestable ear yield of 22.2 t/ha with 55000 plant/ha. Brooking and McPherson (1986) reported 14 sweet corn cultivars ear yield range between 18.7 to 29.2 t/ha with 54000 plant/ha grown in the Manawatu region. Reid et al. (2001b) reported that the potential cob yield of sweet corn grown in Gisbone or Hawke's Bay may reach 30 to 40 t/ha.

As with total dry matter yield, fertiliser P treatments did not influence the sweet corn fresh cobs yields either in the Hawke's Bay or in the Manawatu field experiment. Overall, these two field experiments demonstrate that with Olsen P test of 10-15 mg P /kg soil, it is possible to grow sweet corn with a fresh cob harvestable yield of 27-28 t/ha. Notably a lower sweet corn total plant dry matter yield was produced in the Manawatu (11 v 14 t/ha in the Hawke's Bay), which was probably due to early cold temperatures, which caused late field emergence, and dry summer conditions during the growth period. A similar reduction in sweet corn total plant biomass under water deficit conditions was reported by Stone et al. (2001).

3.4.4 Maize grain yield and response to P fertiliser

On average, the maize grain yields (mean P treatments) at 14% seed moisture content were 16 t/ha (hybrid 34E79) with 87719 plants/ha in the Hawke's Bay and 10 t/ha (hybrid 36H36) with 71124 plants/ha in the Manawatu field experiments (Table 3.8 & 3.15). The optimum plant population for grain yield of maize varies with both cultivar

and environment (Eagles, 1987). In NZ, Douglas et al. (1982) and Dyson and Douglas (1975) obtained maximum grain yields in the range of 80000 to 90000 plants/ha with maize in Poverty Bay and Waikato regions. In the Manawatu, Edmeades (1972) calculated a required population of 92000 plants/ha to attain maximum yields for the maize crop. The highest maize grain yields recorded in the maize yield competition in seven different districts were in the range of 10.8 to 16 t/ha (Steele, 1985). Reid et al. (2001a) reported that actual yields for maize grain in North Island varied from 8.6 to 19.4 t/ha depending on paddock to paddock and year to year variation. Therefore, the actual maize grain yields of 16 and 10 t/ha in these two field trials (Hawke's Bay & Manawatu) were within the reported ranges for commercial crops (Reid et al., 1999a; Reid et al., 2001a). The main reasons for 6 t/ha difference in grain yield between two experiments were most probably the differences in maize cultivar, plant population and the soil water limitation in mid-summer in Manawatu. However, there were no differences in the harvest index (grain as a fraction of crop biomass) between the two maize hybrids (0.47) planted and harvested with different plant populations in two different regions.

Again, the P fertiliser treatments had no significant effect on maize grain yield either in the Hawke's Bay or the Manawatu field experiment (Table 3.8 and Table 3.15). These results are consistent with the recommendations of Reid et al. (2001a), who reported that yield responses to P fertiliser are rare unless the Olsen P levels in the soil is <10 mg P/kg soil. These authors in their experiments across the North Island have found no yield response to P fertiliser at Olsen P test values as low as 8 mg P/kg. Finally, the previous field experiments and these (Hawke's Bay and Manawatu) field experiments reported here demonstrate that there is no need to apply any additional pre-plant or starter P fertiliser to grow a commercial maize grain crop in New Zealand if Olsen P test value is > 11 mg P/kg soil.

3.4.5 Soil P status response to fertiliser P application and crop growth

In reporting lack of yield response to P fertiliser applied to raise soil P status, it is important to confirm that fertiliser P application did indeed raise soil P status for the duration of crop growth. The Olsen P soil test (Olsen et al., 1954) is an indicator used to assess the availability of soil P to plants and when calibrated to crop yield assists the

calculation of the P fertiliser requirement for crops (Kamprath and Watson, 1980; Hedley et al., 1995). The P fertiliser application should be reflected in increases in Olsen P test values. Moreover, P uptake by the maize and sweet corn crops may result in measurable decreases in soil available P status which are reflected by decreases in Olsen P test values with time or crop growth.

At the Hawke's Bay field experiment site, the 100 and 200 kg P/ha treatments caused the Olsen P values of the 0-150 mm soil depth (mean both cultivars) to increase from 14 mg P/kg (control) to 19 mg P/kg (100 kg P/ha) and 36 mg P/kg (200 kg P/ha) at 45 DAS, respectively (Table 3.5). These changes for the plough layer (0-150 mm) represent 1 unit change per 20 kg P/ha and 1 unit per 10 kg P for 100 and 200 kg P, respectively, consistent with the change values reported by NZ Fertiliser Recommendations for Horticultural Crops (1986). In the Manawatu field experiment (80 DAS), the 15 and 70 kg P/ha application raised the mean Olsen P test values of the topsoil 150 mm from 13 mg P/kg (control) to 14 and 16 mg P/kg, changes of 1 unit change per 15 kg P and 1 unit per 25 kg P, respectively (Table 3.11). These increases in Olsen P test values are, however, less than those suggested by NZ Fertiliser Recommendations for Horticultural Crops (1986). Overall, these increases in measured Olsen P test values at both experiment sites caused by fertiliser P addition confirm that the maize and sweet corn crops were initially exposed to marked treatment changes in soil P status.

Monitoring of Olsen P test values at 0-150 mm soil depth with time showed decreases of 4 and 1 mg P/kg soil under maize and sweet corn (control treatment) between 45 to 102 DAS (57 days) at the Hawke'Bay experiment (Table 3.5). In comparison, a decrease of 2 and 3 mg P/kg under maize and sweet corn (control treatment) occurred between 80 to 140 DAS (60 days) at the Manawatu experiment (Table 3.11). The decrease in Olsen P values varied with experiment site, most probably because of the variations in P retention characteristics, texture, fertility and moisture content of the soils. At each site, however, the overall soil P status maintained by each phosphate fertiliser treatment and the changes in Olsen P test values indicated that similar available soil P status were produced for both cultivars. The phosphorus uptake patterns and the change in soil P status during crop growth are discussed in more detail in Chapter 4 and 6.

Despite the fact that the Olsen P test values before planting in both the field experiments (11-13 mg P/kg) were considered marginal for maize and deficient for sweet corn and that marked fertiliser treatment changes in soil P status were produced, there were no significant effects of P fertiliser on the yields of both cultivars in both the experiments. To confirm that neither cultivar was non P-responsive, it was necessary to rule out other factors that may have limited sweet corn growth responses to fertiliser P during those two growing seasons.

3.4.6 Other yield limiting factors for/during crop growth

During both field experiments, the experience gained from planting till harvest suggests that sweet corn was the more sensitive crop with low seed vigour value and can easily be affected by several factors such as sowing time, plant population, air and soil temperature, soil water content and any other soil nutrient deficiencies. Therefore, a possibility is that the lack of P response in sweet corn yields (dry matter and fresh cob) during these two field experiments could be due to late planting in the Hawke's Bay (around 3 weeks) and the dry summer condition in the Manawatu region. Further, the lack of P responsiveness of sweet corn yields (dry matter & fresh cob) could result from the fact that sweet corn growth and yields were constrained by some other influential factors. In this way, the full expression of P responsiveness to growth may be constrained. The other factors that need to be considered and examined are:

- adequate solar radiation for crop growth;
- adequate soil water content during growth;
- soil physical condition for root growth;
- adequate N supply during crop growth;
- any other nutrient deficiencies;

3.4.6.1 Adequate solar radiation

Solar radiation and temperature are two weather variables that have a direct and significant effect on crop production (Muchow et al., 1990; Wilson et al., 1995). Maize is a warm weather crop requiring frost free conditions during the growing period for reliable yields (Berger, 1962). Its growth and development occurs with temperature between 10^0C and 30^0C (Duncan, 1975) with optimal temperature being between 21^0C and 27^0C (Shaw, 1977). In New Zealand, the maximum yield will be obtained by growing a suitable hybrid which occupies the full growing season (Bansal and Eagles, 1985). The studies have recommended that the maize crop should be sown as early as possible in the season by avoiding late frost and soil temperature below 8^0C and to be harvested in May (or before) with seed moisture content below 25% (Hardacre and Eagles, 1989; Hardacre et al., 1991). Sweet corn is normally harvested earlier (January to March) with kernel moisture content around 72% (Brooking and McPherson, 1986).

The growing degree days (GDD) for both the cultivars differed markedly in the two experiments. This was a consequence of differences in the temperatures and date of planting during those two growing seasons 2001-2 and 2002-03. In the Hawke's Bay, the sweet corn (hybrid Challenger) and maize (hybrid 34E79) were harvested at 115 and 182 DAS and accumulated 1068 and 1411 GDD (Table 3.17). In contrast, the sweet corn (hybrid Challenger) and maize (hybrid 36H36) were harvested at 140 and 200 DAS and accumulated 957 and 1324 GDD, respectively in the Manawatu experiment (Table 3.17). A consequence of slow GDD accumulation in the Manawatu experiment is that both cultivars were immature when the large soil water deficit occurred in January and February, 2003. The Manawatu growing season (2002-03) was comparatively cool and dry with an average monthly maximum temperature of 20^0C over the period for November to April compared to 22^0C in the Hawke's Bay during 2001-02 (Table 3.3 & Table 3.9). The maximum and minimum air temperatures during the earlier crop establishment stage were 19.8 and 10.2^0C in the Hawke's Bay (November, 2001) compared to 15.5 and 6.7^0C in the Manawatu (November, 2002) (Table 3.3 and Table 3.9). Lower maximum and minimum temperatures (14.3 and 5.2 ^{0}C, October, 2002) in the Manawatu (Table 3.9) delayed the seedling emergence and affected the initial crop vegetative growth. From November, 2002 (15.5–6.7^0C) to

March, 03 (24.4–12.2^{0}C) temperatures rose to more suitable levels for crop growth in the Manawatu region (Table 3.9).

Strong relationships existed between the GDD (a surrogate for accumulation of solar radiation) and the total dry matter yield (t/ha) in both the field experiments with maize (not shown) and sweet corn (Figure 3.15). The strong linear relationships (R^2=0.99) between GDD and dry matter suggest that available water and nutrient supply did not constrain sweet corn growth, and solar radiation was the main growth limiting factor. The lower slope for the Manawatu experiment indicates that perhaps a second factor influenced sweet corn growth rate could have been soil water stress as mentioned earlier.

Maize is a longer growing season crop compared to sweet corn and the length of maize growing season is usually in the range of 120 days with 1300 -1700 GDD, depending on the cultivar and climatic condition. The maize hybrid 34E79 reached the maturity 15 days earlier and required 87 less GDD in the Hawke's Bay than the maize hybrid 36H36 in the Manatawu area (Table 3.17). In other words, hybrid 34E79 was more efficient than hybrid 36H36 which was reflected by its greater grain and dry matter yield produced in the Hawke's Bay experiment (Table 3.17). Generally, both the maize hybrids reached their maturity during May with seed moisture content around 26-28%, respectively. Overall with maize, there was no such crop physiological disorder symptoms observed in the Hawke's Bay, however, the dry season 2002-03 in the Manawatu, could have limited the P fertiliser responses and reduction in dry matter yield.

Sweet corn has a shorter growing season than maize and the length of the sweet corn growing season is usually in the range of 85-90 days with 1200-1300 GDD (Hanly, 2001), depending on the cultivar grown and the climatic conditions. The sweet corn hybrid Challenger reached maturity 25 days earlier in Hawke's Bay with 111 less GDD compared to the Manawatu experiment (Table 3.17). In other words, the sweet corn hybrid Challenger grew more efficiently in the 2001 Hawke's Bay season. Hardacre et al. (1991) recommended that late maturing hybrids should not be grown in the Manawatu region because when grown there they showed a high incidence of cob rotting and other problems. Thus it is likely that inadequate solar radiation and low

temperatures are the main growth limiting factors which could influence sweet corn biomass response to added P fertiliser.

Table 3.17 Maize and sweet corn crop parameters comparison between regions.

Parameters	Sweet corn		Maize	
	hyb Challenger	hyb Challengar	hyb 34E79	hyb 36H36
	Hawke's Bay (2001-02)	Manawatu (2002-03)	Hawke's Bay (2001-02)	Manawatu (2002-03)
Harvest time (DAS)	115	140	182	200
Plant population (plant/ha)	71124	71124	87719	71124
Dry matter yield (t/ha)	14	11	30	18
Fresh cob yield (t/ha)	27	28	-	-
Fresh cob yield calculator predicated (t/ha)	29	24	-	-
GDD (8°C)	1068	957	1411	1324
Harvest Index	-	-	0.46	0.47
Grain yield at 14% (t/ha)	-	-	16	10

Values in rows/columns are mean for P treatments from Hawke's Bay & Manawatu experiments

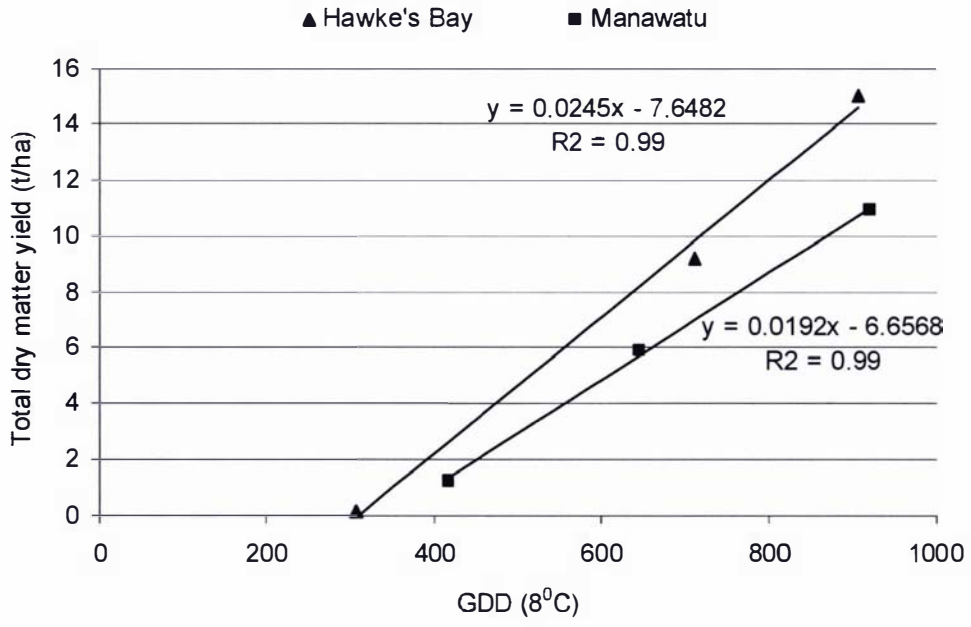


Figure 3.15 Regression analysis for GDD (8^{0}C) and total dry matter yield (mean P treatments) for sweet corn in the Hawke's Bay and Manawatu.

3.4.6.2 Adequate soil water content

A desirable/suitable climate for maize is one in which rainfall is sufficient to wet the soil to field capacity down to root depth before sowing and a rainfall of at least 375 mm during the growing season (Arnon, 1975). In New Zealand, maize and sweet corn yields are reduced when the soil water content drops below 50 and 60% of the available water holding capacity of that soil (Reid et al., 2001a; b). Further, yield of maize and sweet corn drops by 500 and 350 kg/ha for every 10 mm below this drought threshold (Reid et al., 2001a; b). Soil water availability is modelled and discussed further in Chapter 6.

Both the field experiments (Hawke's Bay and Manawatu) were conducted under natural conditions without any irrigation application. Therefore, soil water stored in the root zone before planting and the rainfall during the season were the only sources to meet the crop water requirements. There were significant differences in soil water content among the soil depths and between the two cultivars in both the field experiments (Table 3.4 and Table 3.10). Overall, the soil water content under maize was lower than for sweet corn in the Hawke's Bay field experiment at 102 DAS, and throughout the sampling stages (80, 110 & 140 DAS) in the Manawatu field experiment. This suggests that maize utilised more water from the soil compared to sweet corn for its early growth and development in both experiments.

In the Hawke's Bay field experiment (season 2001-02), the initial (28.11.2001) soil water storage of approximately 140 mm at 0-400 mm soil profile and rainfall of 499 mm (from November, 2001 to April 2002) maintained the soil water content within a range of 0.31 to 0.24 m^3/m^3, which did not result in moisture stress for maize or sweet corn growth in that region. In the Manawatu field experiment (season 2002-03), however, the soil water contents in the root zone were reduced below the critical values (see Chapter 6, section 6.4.3) and remained within a range of 0.29 to 0.19 m^3/m^3, especially during the cob filling period for maize. This corresponded to below average rainfall in months of January, February, March and April, 2003 (Table 3.9). In the Manawatu region, the total amount of rain received from planting (22.10.02) till sweet corn (12.3.03) and maize harvest (15.5.03) were 202 and 264 mm, respectively, which was marginal for crop requirements. Detail discussion on this issue is in Chapter 6. Overall, the dry condition experienced during Manawatu field experiment may have

contributed to limit the P responsiveness during that particular season 2002-03. During a substantial part of that season, the surface soil which contributes the highest P status soil was near permanent wilting point (0.17 m^3/m^3), which would have reduced P absorption. Soil water stress inhibits plant root growth and, in addition, decreases the diffusion of inorganic P to root surfaces and the mineralization of organic P (Hedley et al., 1995). Reduced P responses under low soil water have been reported elsewhere (Simpson and Pinkerton, 1989; Dodd et al., 1992), especially when surface soil water is limiting (Simpson and Pinkerton, 1989).

3.4.6.3 Adequate soil physical conditions

Maize can be grown on a wide variety of soils but performs best on well-drained, aerated, deep, warm loams and silt loams containing adequate organic matter and well supplied with available nutrients (Berger, 1962). At planting a friable tilth and good seed bed for root development and crop growth existed at both the experimental sites. At the Hawke's Bay site, the topsoil texture was clay loam with sandy loam at lower depths. In contrast, at the Manawatu site, the topsoil texture was fine sandy loam with coarse sandy loam at lower depths. Overall, the soil texture at both field experiments (Hawke's & Manawatu) suggests that texture was unlikely to have constrained growth of maize and sweet corn crops during those field experiments.

In both the field experiments, the topsoil dry bulk density values were within the range 0.90 to 1.2 g/cm^3 as reported for recently cultivated topsoil (McLaren and Cameron, 1996). Soil dry bulk density values in this range are unlikely to present any physical constraint to seedling emergence or root penetration; generally compaction begins to constrain the root growth when the bulk density exceeds 1.5 g/cm^3 (Scotter, 1996). The dry bulk densities at 0-400 mm lower soil depth were 0.68 g/cm^3 at the Hawke's Bay and 1.30 g/cm^3 at Manawatu field experiments (Appendix 3.2a). This major contrast in dry bulk densities at lower depths was because the Te Awa soil type (Hawke's Bay site) consists of water deposit (alluvium) from greywacke and/or sandstone, or limestone, overlying Taupo pumice alluvium (Griffiths, 2001). The higher soil porosity values (63 to 77%) in the Hawke's Bay experiment are consistent with the low bulk dry densities and consistent with values reported in the literature for this soil type (NZ Soil Bureau, 1968; McLaren and Cameron, 1996). As soil depth increased, the soil porosity also

increased in the coarse-pumice gravels at 400 mm depth (Appendix 3.2a). These physical soil properties confirm that both sites have natural free draining soils.

At both field experiment sites, the soil physical conditions were favourable in all aspects and were unlikely to have restricted the expression of a sweet corn yield response to applied P fertiliser.

3.4.6.4 Adequate soil N status/requirement

Maize and sweet corn production can be severely limited by N deficiency more often than by any other nutrient. Maize and sweet corn partition more N to their grain than any other nutrient derived from the soil (Steele et al., 1982; Marschner, 1986). Many existing N fertiliser recommendations in NZ are based on grower experiences, fertiliser history and soil N supply, gauged by the number of years a field has been continuously cropped (Steele et al., 1982; Steele, 1985). N supply has a dominant influence on maize and sweet corn yields, but applying excess N is usually uneconomical and increases the risks of nitrate leaching (Reid et al., 2001a; b). For growing maize and sweet corn, Reid et al.(2001a; b) have recommended that N fertiliser is rarely needed if the mineralisable N test (0-150 mm depth) is > 140 kg N/ha for maize and if > 110 kg N/ha for sweet corn. These values are usually found when soils are recently ploughed out of pasture. The general recommended rate of N application for maize in NZ is around 200 kg N/ha (Munir, 2000) and for sweet corn is 100-150 kg N/ha incorporated in soil in two applications (Hansen, 2000).

At the Hawke's Bay field experiment site, the initial mineralisable N values were 49 and 53 kg N/ha for the top 150 mm soil under maize and sweet corn (Table 3.1). These values were below the recommendations (Reid et al., 2001a; b) probably because the site had been continuously cropped for a number of years. Therefore, a week after land preparation, 240 kg N /ha as urea was broadcast and cultivated in as presowing N. At the Manawatu site, 150 kg N/ha were applied at three split doses (50 kg N/ha as pre-plant, 50 kg N/ha each at 42 and 75 days after sowing). This N application at the Manawatu site was made to ensure N did not limit growth as the site was the first cultivation of permanent pasture. Ploughing a pasture soil causes large mineralization of

organic N, and crops rarely show growth responses to additional N (Steele et al., 1982; Steele, 1985). The N fertiliser application (150 kg N/ha) was applied on all treatments/plots irrespective of cultivar or P fertiliser effects/implications.

Furthermore, in the Manawatu field experiment, soil nitrate-N contents were determined during plant growth at the three soil depths (0-150, 150-300 and 300-400 mm) and throughout the sampling period (Table 3.12). At all times mineral NO_3^- (15 to 30 cm depth) exceeded 50 kg N/ha, illustrating that adequate N remained in the soil throughout the plant growing season.

3.4.6.5 Adequate availability of other nutrients

At the Hawke's Bay site the initial soil test for potassium (K), calcium (Ca) and Magnesium (Mg) gave Quick test values of 5, 20 and 77 respectively (Table 3.1), indicating adequate nutrient supply for maize/sweet corn. Similarly, at the Manawatu site, the initial soil test values for K, Ca, Mg and sulphur (S) were 8, 9, 38, and 5, respectively (Table 3.2), showing adequate nutrient supply to grow maize or sweet corn. Response to fertiliser K in maize field experiments has been rare (Douglas et al., 1982; Steele et al., 1981) and regular application of K is not recommended unless the K soil test is less than 5. Therefore, at K value of 5 (at margin) in Hawke's Bay experiment, K fertiliser at rate of 75 kg K/ha as K_2SO_4 was applied as pre-sowing to minimise the risk of K deficiency. Steele et al. (1981) suggested that the low incidence of yield response to K fertiliser, even at relatively low soil test values, indicated an efficient cycling of K within maize crop system. This is consistent with the small amount of K removed in maize grain relative to total K uptake and the release of large amounts of K during stover decomposition near to planting time (Steele, 1985). There is no evidence to support application of Mg to maize crops in NZ and unnecessary application of Mg may depress yield (Steele et al., 1981). Similarly, no increases in grain yield have been reported following S application to maize crops. Although, the amount of S removed in grain is small (0.9 kg/t), the status of maize crops should be monitored if soils have a low S status and particular if fertilisers containing little S are used (Steele et al., 1981). The soil pH values in both field experiments were also within limit range of 5.8-6.0 (Table 3.1 and 3.2) which are adequate for maize growth. In general terms, all the above

nutrients were within the limit range reported in literature and it is very unlikely that they limited P responsiveness to two cultivars growth and yield.

3.5 Conclusions

Maize and sweet corn, two cultivars of *Zea mays* L. species, inherently (genetics) differed in their dry matter yield production in both experiments, and the maize had higher dry matter yield at all growth stages than sweet corn.

Olsen P test values were marginal for growing maize and deficient for sweet corn as per current P fertiliser recommendations. However, neither maize or sweet corn showed a yield response to the P fertiliser applied in field under low soil P status. Fertiliser P application rates raised Olsen P test values in both field experiments under both cultivars.

Other yield limiting factors (soil physical and chemical properties) were unlikely to have constrained sweet corn growth or yield such that it was unable to respond to raised soil P status. The lack of maize and sweet corn yield response both in the Hawke's Bay and Manawatu experiments, when soil P status was elevated above Olsen P test of 10 to $\geq$ 20 mg P/kg soil suggests that commercially viable yields of both cultivars are able to be grown without P fertiliser with Olsen P soil tests in the 10 to 15 mg P/kg soil range.

The hypothesis set for this Chapter was that "maize and sweet corn differ in their responsiveness to P fertiliser in growth and yield" i.e. sweet corn requires higher soil P status compared to maize for growth and yield. These results suggest that hypothesis is incorrect. Under the conditions of these two field experiments, it seems that the two cultivars are non-responsive to P fertiliser. This appears to contradict the recommendations made in the literature for P fertiliser management of maize and sweet corn, and a more detailed examination is required. In the next Chapter, the P uptake characteristics of these crops are compared.

CHAPTER 4

P UPTAKE AND P USE EFFICIENCY OF MAIZE AND SWEET CORN IN THE HAWKE'S BAY AND MANAWATU FIELD EXPERIMENTS

4.1 Introduction

The overall aim of this Chapter was to test the hypothesis formed in Chapter 2, section 2.9 that maize and sweet corn differ in their P uptake, and maize is more P efficient than sweet corn. In this Chapter, maize is compared with sweet corn in terms of the external P efficiency (i.e. which cultivar takes up more P from soil under low soil P status) and internal P efficiency (i.e. which cultivar can grow more dry matter per unit P taken up).

Harvested plant parts, from the Hawke's Bay and the Manawatu field experiments (Chapter 3) were used to investigate the P uptake patterns for maize and sweet corn. As the maize had higher dry matter yield production compared with sweet corn (Chapter 3), it would be expected that maize would also have higher P uptake if the cultivars did not differ in P efficiency. Although there was no response in dry matter yield production to increased P fertiliser application in these two field experiments, it was still possible that plant P uptake may have shown responses to the amount of P fertiliser applied.

Phosphorus use efficiency has been defined by some scientists as the efficiency with which a plant genotype accumulates P at a given soil P status, whereas, other workers have emphasised the P utilisation efficiency; the amount of dry matter produced per unit of P accumulated (Fohse et al., 1988; Clark, 1990; Blair, 1993; Gourley et al., 1994; Hedley et al., 1994; Trolove et al., 1996). Trolove et al. (2003) reviewed the rhizosphere process that can result in externally P efficient plants. They placed much emphasis on root length and root exudation of compounds actively involved in soil P solubilisation. Several studies have used phosphorus use efficiency indexes to compare species and cultivars (Fohse et al., 1988; Hedley et al., 1994; Trolove et al., 1996; Zoysa et al., 1999; Alves et al., 2001; Sigunga et al., 2002). Most studies reported the ability of cultivars to utilise soil and fertiliser P with a view to assess which plant properties may be best exploited by breeders in developing more P efficient cultivars. For example, Alves et al. (2001) studied maize genotypes contrasting in P efficiency. The authors evaluated twelve maize hybrids in four P concentrations in nutrient solution and found

significant differences between hybrids in P efficiency at earlier stage. These differences were closely related to the P contents in the seed rather than the genotypic variability.

When assessing the P efficiency of plants it is essential to ensure that no other factor is influencing plant growth and P uptake. Maize and sweet corn partition more nitrogen (N) to their grain than any other nutrient derived from soil or fertiliser (Steele et al., 1982; Marschner, 1986). This is probably because N is an essential nutrient for growth and reproduction, and plays a major role in the development/functions of protoplasm (it is a constituent of all proteins). Thus, the N status of maize plants can influence P uptake and vice versa (Arnon, 1975). Therefore, the plant tissue N and P concentration were measured concurrently in the Manawatu experiment in order to help interpret P uptake patterns.

4.2 Materials and Methods

4.2.1 Plant tissue phosphorus (P) and nitrogen (N) content

Samples for plant tissue nutrient P analysis were taken from the harvested plant parts at 33, 75 and 100 DAS in the Hawke's Bay experiment and for both nutrient (P & N) at 80, 110 and 140 DAS in the Manawatu experiment (detail about sampling in Chapter 3, section 3.26). Plant N concentrations were measured only at the final maize grain harvest in the Hawke's Bay experiment. As explained in Chapter 3, full plants were divided into leaves, stem with tassel, tillers, and cobs (including husks). The leaves were further divided into three cohorts as explained in Chapter 3, section 3.2.6. Plant leaves were dried at 70 ^{0}C for approximately 72 hours to obtain dry weight, whereas the stem and cobs were dried for 2-3 weeks to achieve dry weight. The dried material was then passed through an electric plant chopper and sub- samples were collected and ground finely with a hammer mill (sieve size of 1 mm). Total P and N in herbage samples were analysed using a Kjeldahl digest method adapted from the method described by McKenzie and Wallace (1954). This method involved accurately weighing 0.1 g of finely ground herbage onto a piece of cigarette paper (glue strip removed), which was then placed into 100 ml Pyrex^{tm} tube. Kjeldahl digest mixture (4ml) was added to each tube, which was then heated in an aluminium block at 350 ^{0}C for 7 hours. When cooled, the mixture was made up to a volume of 50 ml with deionised water and

thoroughly stirred. The concentrations of P and N in the diluted digest mixture were determined using a Technicon II auto-analyser (Technicon, 1976).

4.2.2 Phosphorus use efficiency

Phosphorus use efficiencies are of two types: external and internal P efficiency. External P efficient mechanisms enable plants to yield more because of an increased ability to extract P from soil, whereas, internal P efficient mechanisms enable a plant to produce more dry matter from a given amount of P absorbed.

External P efficiency (E_{PE}) is calculated as kg P taken up per hectare (Hedley et al., 1994). In order to differentiate plants with enhanced P absorption some researchers (Gourley et al., 1994) examined the ratio of kg P taken up: root mass (or root length). This particular index is examined further in Chapter 5. Internal P efficiency (E_{PI}) is calculated as the amount of dry matter yield produced per unit of P taken up by the plant (Baligar et al., 1990; Hedley et al., 1995).

$$E_{PI} = TDM/P_{uptake} \qquad \text{(equation 4.1)}$$

where; TDM = total dry matter yield (kg/ha) & P_{uptake} = P taken up (kg P/ha)

Provided plant tissue P concentrations do not drop into the deficient range, phosphorus use efficiency is a useful index of the internal efficiency with which the plant uses P to produce yield (Alves et al., 2001; Trolove et al., 2003). Low values may indicate surplus P supply relative to some other growth limiting factors.

4.2.3 Statistical analyses

Statistical analyses were performed using the General Linear Model (GLM) software of the Statistical Analysis System (SAS Institute, 1999-2001). Data were analysed by Analysis of Variance (ANOVA) for a 2 x 3 factorial arrangement. Least significant differences (LSD) at 5% were used to detect differences (among means) between cultivars and P fertiliser treatments.

4.3 Results

4.3.1 Hawke's Bay field experiment season 2001-02

4.3.1.1 P uptake at 33, 75 and 100 DAS

The P fertiliser application rates of either 100 or 200 kg P/ha caused significant increases in total P uptake above the control by both cultivars at 75 and 100 DAS. However, at 33 DAS there was no effect of P fertiliser application rate on P uptake. Total P uptake (mean of all P treatments) by maize was 57% higher than sweet corn at 33 DAS and 19% higher at 75 DAS. At 100 DAS, however, there were no significant differences between the total P uptake by maize and sweet corn (Table 4.1). In this field experiment, P uptake by maize and sweet corn were 25 and 21 kg P/ha respectively in the first 75 DAS, with an additional uptake of 12 and 11 kg P/ha respectively between 75 and 100 DAS.

Partitioning of P in plant parts differed between cultivars. In maize, leaves and stem (including tassel) contained proportionally more of the plant P taken up than in sweet corn (Figure 4.1 & 4.2). In contrast, sweet corn tillers and cob including husk contained proportionally more P than the same maize plant parts at 75 and 100 DAS. At final maize harvest (182 DAS), the total P and N found in maize grain was 31 kg P/ha and 220 kg N/ha (Appendix 4.4a). No differences were observed in maize grain P content between P fertiliser treatments.

Table 4.1 Total P uptake by maize and sweet corn at 33, 75 and 100 DAS in the Hawke's Bay field experiment during 2001-02 season.

Treatment	Total P uptake (kg P/ha)					
	33 DAS		75 DAS		100 DAS	
P rate (kg P/ ha)	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	0.83 a	0.45 a	22 a	19 a	32 a	27 a
100	0.90 a	0.48 a	29 b	22 b	37 ab	30 a
200	0.76 a	0.65 a	25 ab	23 b	41 b	39 b
Mean	0.83 a	0.53 b	25 a	21 b	37 a	32 a
LSD (0.05)	0.23		1.2		5.4	
Significance						
cultivars	s		s		ns	
fertiliser	ns		s		s	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05). LSD is for cultivars

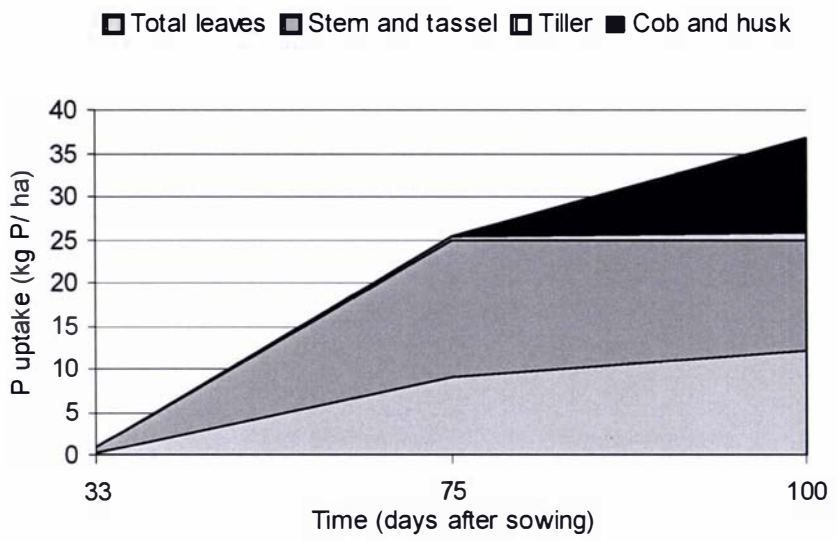


Figure 4.1 Maize P uptake and partitioning (kg P/ha) at 33, 75 & 100 DAS during 2001-02 season in the Hawke's Bay experiment. Results are presented as the mean of 3 P treatments. Detailed data with statistical analyses are in Appendix 4.1a,b,c.

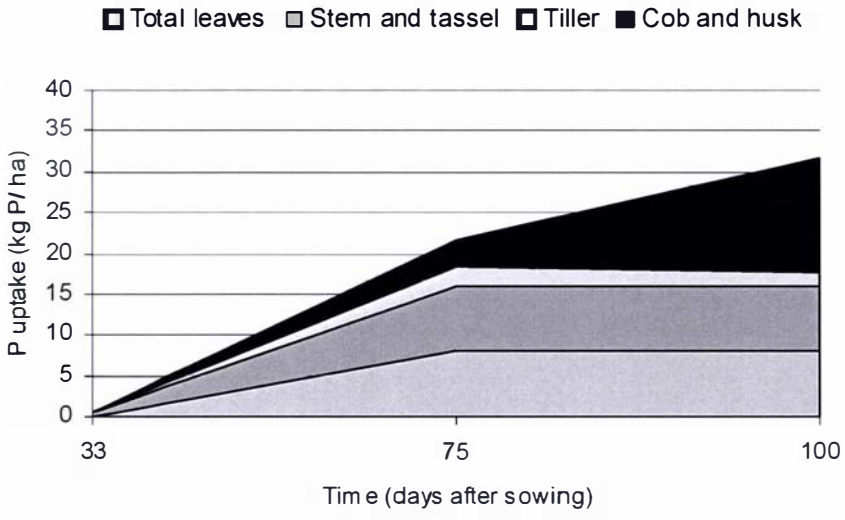


Figure 4.2 Sweet corn P uptake and partitioning (kg P/ha) at 33, 75 & 100 DAS during 2001-02 season in the Hawke's Bay experiment. Results are presented as the mean of 3 P treatments. Detailed data with statistical analyses are in Appendix 4.1a, b,c.

4.3.1.2 Plant tissue P concentration

There were differences in the mean tissue P concentrations (total leaves, stem with tassel, and cob including husks) between maize and sweet corn at different sampling stages (Table 4.2). Overall, the plant tissue P concentrations decreased with time with both cultivars. Maize and sweet corn stem tissue P concentrations were higher than leaves at 33 DAS. At 100 DAS with both maize and sweet corn, P application rates of 100 and 200 kg P/ha increased plant tissue P concentrations in leaves & stem with tassel, but not with the cob with husk.

At 182 DAS (final maize harvest), the maize grain N and P concentrations were found to be 2.2 % and 0.22 %, respectively. There were no significant differences between P fertiliser treatments in final maize grain N and P concentrations (Appendix 4.4b).

Table 4.2 Maize and sweet corn plant P concentration in the Hawke's Bay experiment.

Time (DAS) & Cultivars	Plant tissue P concentration (%)		
	Total Leaves	Stem with tassel	Cob with husk
33 DAS			
Maize	0.33 a	0.52 a	-
Sweet corn	0.29 b	0.51 a	-
LSD	0.03	0.03	-
Significance			
cultivars	s	ns	-
fertiliser	ns	ns	-
75 DAS			
Maize	0.23 a	0.19 a	-
Sweet corn	0.25 b	0.16 b	0.34
LSD	0.02	0.02	-
Significance			
cultivars	s	s	s
fertiliser	ns	ns	ns
100 DAS			
Maize	0.24 a	0.11 a	0.25 a
Sweet corn	0.21 b	0.12 a	0.28 b
LSD	0.01	0.01	0.02
Significance			
cultivars	s	ns	s
fertiliser	s	s	ns

Values in columns are mean for three P treatments and followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

4.3.1.3 Phosphorus use efficiency at 33, 75 and 100 DAS

At 33 and 75 DAS, no significant (P=0.05) differences between the two cultivars were found in the mean internal P use efficiency (E_{PI}) (Table 4.3). However, at 100 DAS, the E_{PI} for maize was 23% higher than sweet corn. In general terms, the E_{PI} increased with time for both cultivars.

There were no significant differences in E_{PI} between P fertiliser treatments at the earlier crop growth stage (33 DAS), but significant differences were found at 75 and 100 DAS. For both cultivars, the E_{PI} values decreased under 100 and 200 kg P/ha treatments compared with the unfertilised P treatment (Table 4.3). Higher P application rates increased P uptake but did not produce significantly higher yields.

Table 4.3 Maize and sweet corn internal P use efficiency (E_{PI}) at 33, 75 and 100 DAS during 2001-02 season in the Hawke's Bay experiment.

Treatment P rate (kg P/ha)	E_{PI} (kg DM /kg P uptake)					
	33 DAS		75 DAS		100 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	217 a	223 a	490 a	482 a	627 a	526 a
100	211 a	224 a	434 b	416 b	559 b	455 b
200	249 a	210 a	427 b	398 b	543 b	432 b
Mean	226 a	219 a	451 a	432 a	577 a	471 b
LSD (0.05)	38		30		24	
Sig ificance cultivars	ns		ns		s	
fertiliser	ns		s		s	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

4.3.2 Manawatu field experiment season 2002-03

4.3.2.1 P uptake at 80, 110 and 140 DAS

At 80 and 110 DAS, the total P uptake (mean of all P treatments) was significantly higher in maize than sweet corn (Table 4.4). However, at 140 days, there was no significant difference between the total P uptake by maize and sweet corn. In this field experiment, the P uptake by maize and sweet corn were 13 and 10 kg P/ha in the first 110 DAS, with an additional uptake of 6 and 8 kg P/ha between 110 and 140 DAS, respectively. Differences in P fertiliser application rate did not significantly influence the total plant P uptake of either cultivar (Table 4.4).

As in the Hawke's Bay experiment, partitioning of P in plant parts differed between cultivars. At 80 & 110 DAS, maize leaves and stem with tassel contained proportionally more of the plant P taken up than sweet corn leaves and stem with tassel. At 140 DAS, there were no significant differences in P partitioning between cultivars. Figure 4.3 & 4.4 represent the P uptake and partitioning by maize and sweet corn plant components.

At 200 DAS (final maize harvest), the total P uptake by maize grain was found to be 20 kg P/ha and no significant differences were observed between P fertiliser treatments (Appendix 4.4c).

Table 4.4 Total P uptake by maize and sweet corn at 80, 110 and 140 DAS in the Manawatu experiment during the season 2002-03.

Treatment	Total P uptake (kg P/ha)					
	80 DAS		110 DAS		140 DAS	
P rate (kg P/ha)	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	7 a	3 a	13 a	9 a	18 a	17 a
15	5 b	3 a	11 a	10 a	20 a	16 a
70	6 a b	4 a	14 a	12 a	18 a	20 a
Mean	6 a	3 b	13 a	10 b	19 a	18 a
LSD (0.05)	0.68		1.86		2.4	
Significance						
cultiva	s		s		ns	
fe tilise	ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

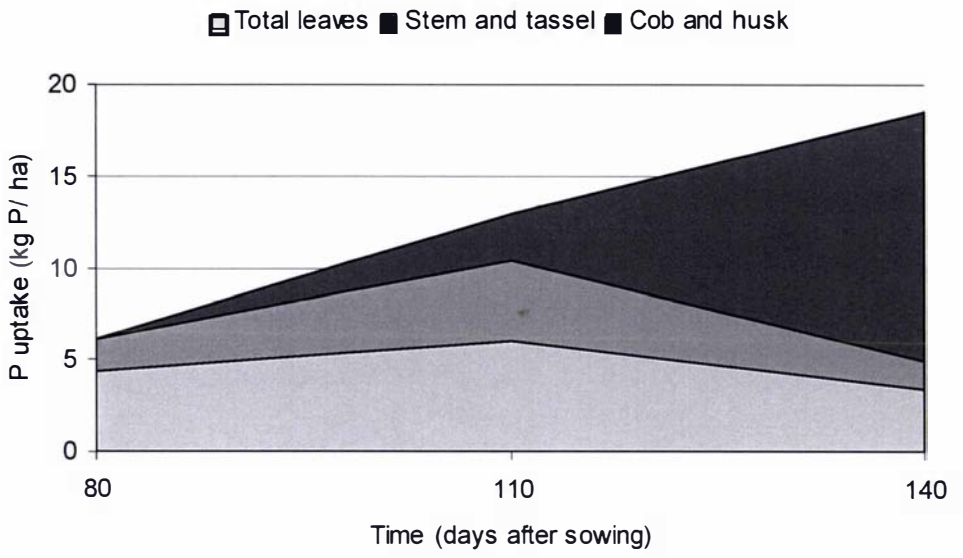


Figure 4.3 Maize P uptake and partitioning (kg P/ha) at 80, 110 & 140 DAS during 2002-03 season in the Manawatu experiment. Results are presented as the mean of 3 P treatments. Detailed data with statistical analyses are in Appendix 4.2a,b,c.

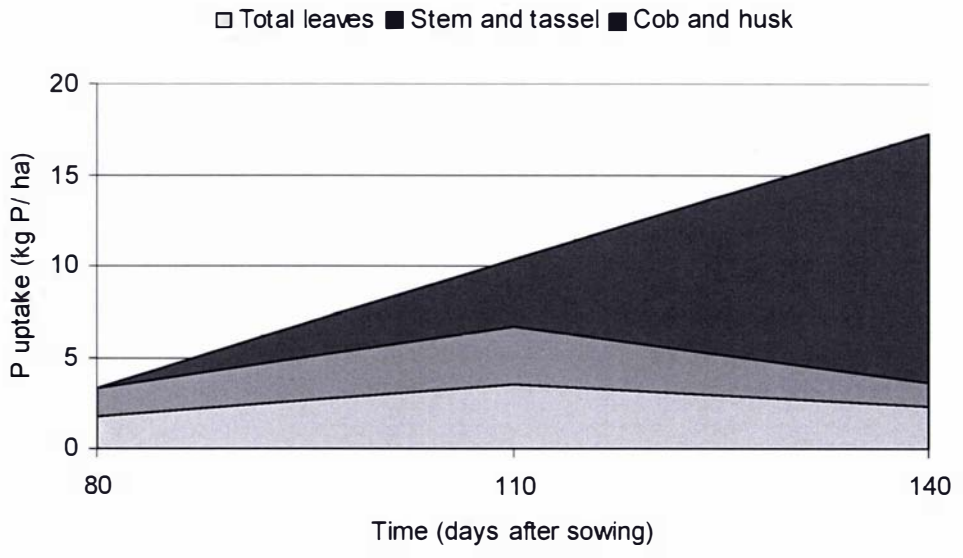


Figure 4.4 Sweet corn P uptake and partitioning (kg P/ha) at 80, 110 & 140 DAS during 2002-03 season in the Manawatu experiment. Results are presented as the mean of 3 P treatments. Detailed data with statistical analyses are in Appendix 4.2a,b,c.

4.3.2.2 Plant tissue P concentration

As in the Hawke's Bay experiment, there were significant differences in the mean tissue P concentrations (total leaves, stem with tassel and cob including husks) between maize and sweet corn at different sampling stages (Table 4.5). Overall, the plant tissue P concentration decreased with time with both cultivars. At 140 DAS, the P tissue concentration in total leaves and stem with tassel were very low in both the cultivars.

There were no significant effects of P fertiliser treatments on plant tissue P concentrations (total leaves, stem with tassel, and cob including husk) on either cultivar. At 200 DAS (final maize harvest), the maize grain N and P concentrations were found to be 2.0% and 0.20 %, respectively. Different P fertiliser application rates caused no significant differences in final maize grain P and N concentrations (Appendix 4.5d).

Table 4.5 Maize and sweet corn plant P concentration during growth in the Manawatu field experiment in the season 2002-03.

Time (DAS) & Cultivars	Plant P concentration (%)		
	Total Leaves	Stem with tassel	Cob with husk
80 DAS			
Maize	0.24 a	0.18 a	N/A
Sweet corn	0.22 b	0.31 b	N/A
LSD	0.01	0.02	-
Significance			
cultivar	s	s	
fertiliser	ns	ns	
110 DAS			
Maize	0.21 a	0.09 a	0.30 a
Sweet corn	0.23 b	0.11 b	0.27 b
LSD	0.02	0.01	0.02
Significance			
cultivar	s	s	s
fertiliser	ns	ns	ns
140 DAS			
Maize	0.13 a	0.03 a	0.17 a
Sweet corn	0.14 a	0.04 a	0.23 b
LSD	0.02	0.006	0.01
Significance			
cultivar	ns	ns	s
fertiliser	ns	ns	ns

Values in columns are mean for three treatments for both cultivars and followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

4.3.2.3 Phosphorus use efficiency at 80, 110 and 140 DAS

At 80, 110 and 140 DAS, maize had higher mean internal P use efficiency (E_{PI}) compared with sweet corn (Table 4.6). The E_{PI} increased with time under both cultivars. During all the sampling periods, no significant differences in E_{PI} were found between P fertiliser treatments with sweet corn, however some minor but significant changes were noted with maize (Table 4.6).

Table 4.6 Maize and sweet corn internal P use efficiency (E_{PI}) at 80, 110 and 140 DAS during 2002-03 seasons in the Manawatu experiment.

Treatment P rate (kg P/ha)	E_{PI} (kg DM /kg P uptake)					
	80 DAS		110 DAS		140 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	456 ab	391 a	677 ab	607 a	862 a	646 a
15	477 b	427 a	726 b	551 a	842 a	644 a
70	429 a	385 a	619 a	574 a	808 a	614 a
Mean	454 a	401 b	675 a	578 b	837 a	634 b
LSD (0.05)	26		41		49	
Significance cultivar fertiliser	 s ns		 s ns		 s ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

4.3.2.4 N uptake at 80, 110 and 140 DAS

The total plant N uptake (mean of all P treatments) was higher with maize than sweet corn (Table 4.7). No significant differences in N uptake were caused by P fertiliser treatments with either cultivar (Table 4.7). In maize, leaves and stems with tassel had significantly higher N uptake than in sweet corn at 80, 110 and 140 DAS (Figure 4.5 & 4.6). However, sweet corn cobs with husk had higher N uptake than maize at 110 DAS (36%). At 140 DAS, there were no differences between maize and sweet corn in N contained in cobs with husk.

At 200 DAS (final maize harvest), the total amount of N in maize grain was found to be 202 kg N/ha. No significant differences were observed in maize grain N contents or N uptake between P fertiliser treatments (Appendix 4.4c,d).

Table 4.7 Total N uptake by maize and sweet corn at 80, 110 and 140 DAS during the 2002-03 season in the Manawatu experiment.

Treatment P rate (kg P/ha)	Total N uptake (kg N/ha)					
	80 DAS		110 DAS		140 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	85 a	40 a	145 a	98 a	176 a	161 a
15	71 b	39 a	132 a	108 a	189 a	145 a
70	80 a b	44 a	143 a	117 a	169 a	178 a
Mean	79 a	41 b	140 a	108 b	178 a	161 b
LSD (0.05)	7.8		16.1		15.0	
Significance cultivars fertiliser	s ns		s ns		s ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

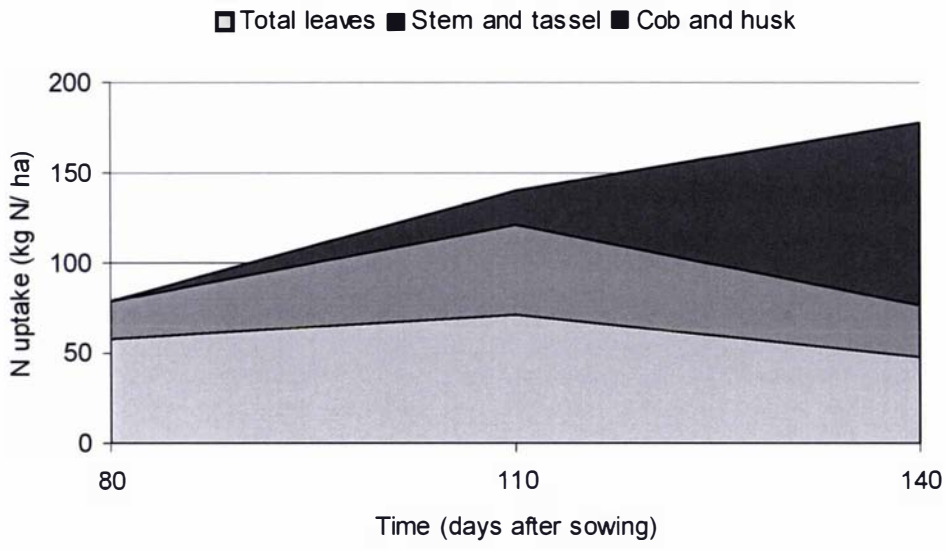


Figure 4.5 Maize N uptake and partitioning (kg N/ha) at 80, 110 and 140 DAS during 2002-03 season in the Manawatu experiment. Results are presented as mean of 3 P treatments. Detailed data with statistical analyses are in Appendix 4.3a,b,c.

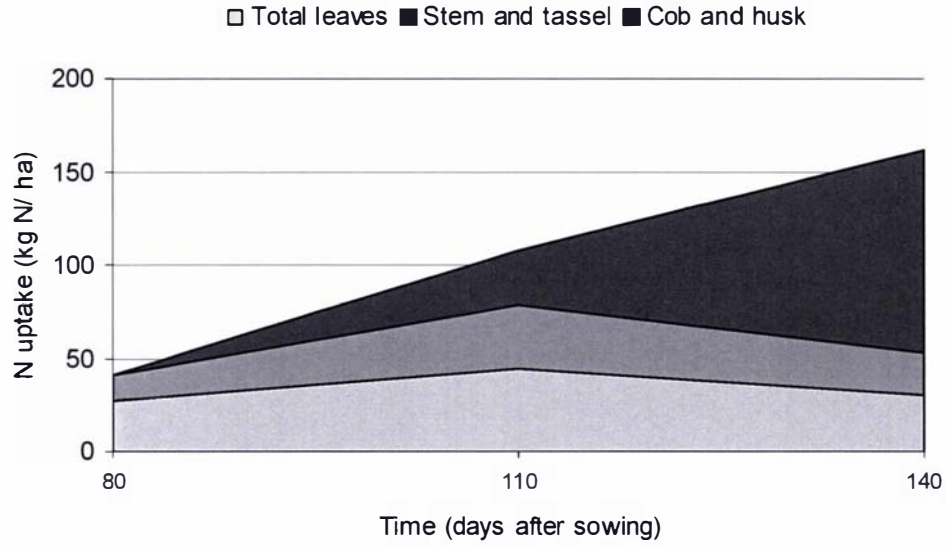


Figure 4.6 Sweet corn N uptake and partitioning (kg N/ha) at 80, 110 and 140 DAS during 2002-03 season in the Manawatu experiment Results are presented as mean of 3 P treatments. Detailed data with statistical analyses are in Appendix 4.3a,b,c.

4.3.2.5 Plant tissue N concentration

There were differences in the mean tissue N concentrations (total leaves, stem with tassel and cob with husks) between maize and sweet corn at particular growth stages (Table 4.8). Like P, the plant tissue N concentration also decreased with time for both cultivars. At 140 DAS, the N tissue concentration in total leaves and stem with tassel were very low with both cultivars. However, there was no effect of P treatments on plant tissue N concentrations (mean all P treatments) in either of the two cultivars during the three sampling stages.

At 200 DAS (final maize harvest), the maize grain N concentration was 2.0%. Phosphorus fertiliser application rate caused no significant differences in final maize grain N concentrations (Appendix 4.4d).

Table 4.8 Maize and sweet corn plant N concentration during growth in the Manawatu field experiment (season 2002-03).

Time (DAS) & Cultivars	Plant N concentration (%)		
	Total Leaves	Stem with tassel	Cob with husk
80 DAS			
Maize	3.4 a	2.1 a	N/A
Sweet corn	3.4 a	3.2 b	N/A
LSD	0.10	0.19	-
Significance			
cultivar	ns	s	-
fertiliser	ns	ns	-
110 DAS			
Maize	2.5 a	0.9 a	2.2 a
Sweet corn	2.8 b	1.1 b	2.2 a
LSD	0.14	0.26	0.14
Significance			
cultivar	s	s	ns
fertiliser	ns	ns	ns
140 DAS			
Maize	1.8 a	0.6 a	1.3 a
Sweet corn	2.0 b	0.6 a	1.9 b
LSD	0.16	0.07	0.07
Significance			
cultivar	s	ns	s
fertiliser	ns	ns	ns

Values in columns are mean for three treatments for both cultivars and followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

4.3.2.6 Nutrient N: P ratios at 80, 110 and 140 DAS

As noted above there were no significant effects of P fertiliser treatments on the total N and P uptake (Table 4.4 and 4.7) by either maize or sweet corn. Therefore, the values for each replicate/treatment (for N and P uptake) were used to calculate the N:P ratio during the three selected stages of crop growth. There were no significant differences between the mean N:P ratios of the two cultivars across all P treatments values (Table 4.9). Overall the N:P ratio decreased with time for both cultivars, which indicated that the plant N concentrations declined faster with time compared with P concentrations for both cultivars.

Table 4.9 Summary of nutrient ratio (N: P) calculated from maize and sweet corn crop grown during 2002-03 season in the Manawatu.

Treatment P rate (kg P/ha)	N:P ratio					
	80 DAS		110 DAS		140 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	12.9	12.9	10.9	10.6	9.8	9.5
15	13.4	13.0	11.6	10.5	9.6	9.2
70	12.5	12.6	10.0	10.1	9.3	9.0
Mean	12.9 a	12.8 a	10.8 a	10.4 a	9.6 a	9.2 a
LSD (0.05)	0.43		0.60		0.52	
Significance cultivars	ns		ns		ns	
fertiliser	ns		ns		ns	

Means values within rows (cultivars) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

4.4 Discussion

4.4.1 P uptake and response to P fertiliser

In both field experiments (Hawke's Bay and Manawatu), similar trends in P uptake occurred. Compared with sweet corn, maize had significantly higher P uptake (kg P/ha) at plant establishment and vegetative stages; allocating more P to leaves and stems (Table 4.1 and 4.4). It is often stated in the literature (Nye and Tinker, 1977; Barber, 1984; Tinker and Nye, 2000) that the limiting factor in P uptake is the rate of diffusion of P to active root surfaces, and this will be influenced by the phosphate concentration in the soil. In the Manawatu experiment, increasing P concentration in the soil with P fertiliser had little effect on P uptake, most likely because of the climatic conditions i.e. low temperature at crop establishment and soil water stress at later crop growth stages. P uptake rates are highly dependent on soil water filled pore space, particularly approaching values near wilting point (Barber, 1962; Barber and Cushman,1981; Barber and Silberbush, 1984).

The initial greater uptake of P by maize than sweet corn was probably associated with the faster earlier growth and a greater allocation of biomass to root growth (Chapter 3, Table 3.7 and 3.14). Furthermore, maize appeared to have a greater internal P efficiency in both experiments (Table 4.3 and 4.6). Although at the time of sweet corn maturity the total P uptake by the sweet corn had caught up to that of maize, there were still significant differences in dry matter yields (4-6 t/ha) between the two cultivars. The similarity in total P uptake between the cultivars at the time of sweet corn maturity is possibly related to this particular sweet corn hybrid developing earlier cobs and tillers than the maize hybrid used in those experiments. Some studies have also reported that early maturing maize varieties tended to accumulate greater amounts of P than later maturing maize varieties (Bruetsch and Estes, 1976).

In New Zealand, Steele (1985) reported that a 12 t/ha maize grain crop (14% moisture) contains about 40 kg P in grain. Similarly, Reid et al. (2001a) reported that a typical maize grain crop (15 t/ha) absorbs about 65 kg P/ha with approximately 45 kg P/ha residing in the grain at harvest. The amounts of P removed in maize grain at the Hawke's Bay (31 kg P/ha) and Manawatu (20 kg P/ha) experiments are slightly below

the amounts suggested by Steele (1985) and Reid et al. (2001a). Lower P uptake was a function of both lower yield and lower plant P content than the values suggested. It is known from the literature review that the amount of P accumulation depends on the general nutrient status of soil type and climatic characteristics. Therefore, the variation in P uptake between literature values and the current experiments are likely to be caused by field site differences in climatic characteristics and soil fertility. Furthermore, this study provides evidence of seasonal and site variations in P uptake. The lower amount of P accumulation in maize grown in the Manawatu experiment was probably caused by the relatively cold temperatures early in the season (2002) at planting and dry summer conditions (2003) later in the reproductive stages. This ultimately reduced the P uptake with both cultivars.

In both experiments, the total plant P uptake by mature sweet corn was 32 and 18 kg P/ha in the Hawke's Bay (100 DAS) and Manawatu (140 DAS) sites, respectively (Table 4.1 & 4.4). However, the final P content in sweet corn kernels was not measured. Hanly (2001) reported the P uptake by sweet corn ranged from 11-19 kg P/ha under Olsen P test values of 11-45 mg P/ha in the Gisborne region. Reid et al. (2001b) suggested that a typical 25 t/ha fresh cob sweet corn crop absorbs about 24 kg P/ha. The P uptake values found in these two field experiments are within the range of those reported values. As explained earlier, P uptake is dependent upon soil and climatic characteristics. Therefore, this variation in P uptake values with sweet corn is not unexpected and probably explains the differences in the amount of P taken up by sweet corn between the two sites.

In the Hawke's Bay experiment, approximately 67 % and 33 % of total P accumulation with both cultivars occurred in the 0-75 and 76-100 DAS periods. In the Manawatu experiment, around 32 and 17 % of total P accumulation in maize and sweet corn occurred between 0-80 DAS, and approximately 38% for both cultivars between 81 to 110 DAS; with a further 32 % by maize and 44% by sweet corn between 111-140 DAS (Table 4.10). This indicates that active P uptake continued untill the final harvest with both cultivars. This is consistent with other studies (Berger, 1962; Aldrich and Leng, 1969; Ritchie, 1997) in which maize accumulated P throughout the growing season till the final harvest. The highest proportion (67%) of total P uptake was taken up during the crop vegetative stage (0-75 DAS) in the Hawke's Bay experiment under moist

conditions, whereas only 38% was taken up in the Manawatu (110 DAS) experiment under dry conditions (Table 4.10). These differences illustrate how plant growing conditions have a marked influence on the timing and the amount of P taken up.

Table 4.10 The percentage of total P taken up (%) by maize and sweet corn at different growth intervals in the Hawke's Bay and Manawatu experiments.

Hawke's Bay (2001-02)	0-33 DAS	34-75 DAS	76-100 DAS
Maize	2 (0.83 kg P/ha)	65 (25 kg P/ha)	32 (37 kg P/ha)
Sweet corn	2 (0.53 kg P/ha)	64 (21 kg P/ha)	34 (32 kg P/ha)
Manawatu (2002-03)	0-80 DAS	81-110 DAS	111-140 DAS
Maize	32 (6 kg P/ha)	37 (13 kg P/ha)	32 (19 kg P/ha)
Sweet corn	17 (3 kg P/ha)	39 (10 kg P/ha)	44 (18 kg P/ha)

values in rows/columns are mean for t ree (Hawke's Bay) and five (Manawatu) treatments

It is noted that the P uptake by sweet corn is consistently less than that of maize, however, these differences are small compared with the substantial differences between the two experiments. After 500 degree days and onward, the P uptake per degree day in the Hawke's Bay experiment was approximately twice that in the Manawatu (Figure 4.7). This clearly demonstrates that weather or edaphic factors limited P uptake by the crops grown in the Manawatu. Various regression functions were used to evaluate the relationship between total P uptake (mean of 3 P treatments) and thermal time (calculated from GDD) to compare P uptake differences at the two experiments sites. The sigmoid growth model (sigmoid curve) fitted best (R^2=1) with the following equation.

$$Y = a\,(1 + be^{-ct})^{-1} \qquad \text{(equation 4.1)}$$

where; a = maximum yield; b = curvature coefficient; c = growth rate and t = thermal time in ^{0}Cd. The differences in P uptake occurred in the vegetative growth stages (from 500 to approximately 850 ^{0}Cd). For this period there were marked differences (>20%) in total P uptake between locations for both cultivars (Figure 4.7). For example, between 640 - 840 ^{0}Cd the rate of P uptake for sweet corn (71124 plants/ha) in the Manawatu averaged 0.07 kg P/ha/ ^{0}Cd, which was 58% lower than the value of 0.12 kg P/ha/ ^{0}Cd for sweet corn in the Hawke's Bay. This explains that as thermal time increased in the drought-affected Manawatu experiment, the expansion of the root system (which could be expected to increase P uptake) occurred in an increasingly dry soil, the latter which would restrict P movement through the soil to the roots. Such possibilities are discussed further in Chapter 6. Similar comparisons between experiments are possible for maize but they are difficult to interpret because of the difference in plant population between the two locations.

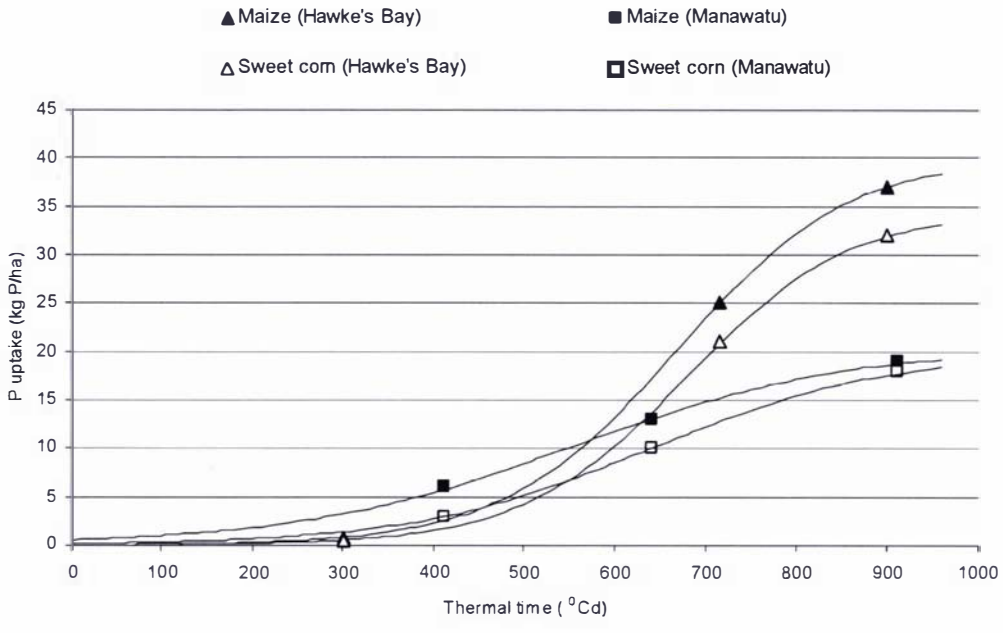


Figure 4.7 The relationship between total plant P uptake (mean P 3 treatments) and accumulated thermal time for both cultivars in the Hawke's Bay and Manawatu experiments; Sigmoid curve fits for sweet corn P uptake. Hawke's Bay $Y=35\ (1+1861e^{-0.0111t})$ & Manawatu $Y=20\ (1+138e^{-0.0077t})$

4.4.2 Plant tissue P concentrations

The concentration of most nutrients varies between plant parts and with the physiological stage of development. Interpretation of plant tissue P concentration is sometimes difficult unless the part and age of the plant analysed are clearly defined. The optimum nutrient concentrations for maize grown in New Zealand refers to the ear leaf sampled at tasseling (Cornforth and Steele, 1981). In the current study, maize and sweet corn nutrient concentrations were measured when dry matter yields were measured, and are discussed accordingly.

In both field experiments (Hawke's Bay and Manawatu), the plant tissue P concentration varied between plant components (leaves, stem with tassel and cob with husk) with both cultivars (Table 4.2 and 4.5). This is quite normal as plant parts differ in their structure and function with respect to physiological changes during their development. There were significant differences in P concentrations within plant components at different growth intervals between the two cultivars (Table 4.2 and 4.5). Although maize had a higher dry matter yield, it also had higher P concentrations in non-reproductive parts e.g. leaves (Table 4.2 and 4.5). In general, the maize leaf P concentrations were significantly greater than those of sweet corn in both field experiments. An exception was at 140 DAS in the Manawatu region. In both experiments, the decrease in P concentration in leaves and stem (including tassel) with time indicates that P is remobilised and transferred to the reproductive portion i.e. grains (Table 4.2 & 4.5).

The total leaf mean P concentrations for maize and sweet corn ranged from to 0.21 and 0.33% (Hawke's Bay) and 0.13 and 0.24% (Manawatu) at different growth/development stages (Table 4.2 and 4.5). In NZ, the optimum P concentration of maize ear leaf sampled at tasselling is considered to be ranged between 0.18 to 0.32% (see reviews by Cornforth and Steele, 1981; Reid et al., 2001a; b). Other literature suggests that if the percentage of P exceeds 0.25%, the P concentration of a plant is considered sufficient. However, if the P concentration is less than 0.20%, the plant is considered to be low in P, and if less than 0.10%, the plant is considered to be very deficient (Hanway and Olsen, 1980). In both the field experiments, the total leaf P concentrations were within the optimum range at different growth stages of both

cultivars, except at 140 DAS in the Manawatu. This suggests that P supply was adequate to maintain the nutritional status of both maize and sweet corn during the two seasons. This is supported by the absence of significant yield responses to P fertiliser. However, the P concentration value of 0.13% in the Manawatu field experiment at 140 DAS suggests that P deficiency may have occurred at that particular stage with both cultivars, which is most probably due to the limited soil water content between 110 and 140 DAS, as explained earlier. Therefore, for most of the growing season both cultivars did not display leaf P concentrations indicative of P deficiency, despite growing on the unfertilised soil with Olsen P levels of 13 and 11 mg P/kg soil.

Factors such as plant variety, climatic or soil physical conditions may influence both actual and required concentrations of nutrients in plants (Cornforth and Steele, 1981). There was a marked difference in the total P uptake by maize and sweet corn between the two experiments (Table 4.1 and 4.4). Hence, marked differences in total leaf P concentrations at the Hawke's Bay (100 DAS) and Manawatu (140 DAS) were observed. However, there was no significant difference in the mean total leaf P concentration among the P fertiliser treatments in the Manawatu field experiment, whereas, some differences were found with both cultivars having greater leaf concentrations with P fertiliser treatments (200 = 100 > 0 kg P/ha) in the Hawke's Bay experiment at 100 DAS. The reason for the lack of response to applied P in the Manawatu experiment is probably the late season dry soil conditions compared with the Hawke's Bay favourable season (where the soil water remained adequate during crop growth).

4.4.3 N uptake and response to P fertiliser

In the Manawatu field experiment (season 2002-03), the total plant N uptake by both cultivars generally increased as the plant dry matter increased. Maize had a significantly higher total N uptake at all sampling times (80, 110 and 140 DAS) compared to that of sweet corn (Table 4.7). These results were consistent with the soil N (nitrate-N) results obtained in Chapter 3 (section 3.3.2.4), which showed that maize reduced soil nitrate contents significantly more than sweet corn between 80-140 DAS. High N uptake by maize corresponded to its greater biomass (dry matter yield) compared with sweet corn. Hence, maize has a greater demand for N than sweet corn. Other New Zealand studies

have also reported that maize and sweet corn cultivars differ in their N fertiliser requirement or N uptake (Hansen, 2000; Munir, 2000).

In the Manawatu experiment at 140 DAS (sweet corn maturity stage), the total plant N uptake by maize (178 kg N/ha) was significantly (P=0.05) higher compared with sweet corn (161 kg N/ha). At 200 DAS (final maize harvest), the maize grain contained 202 kg N/ha with a 10 t/ha grain yield (14% moisture, 2.0%N). In New Zealand, Steele et al. (1981) reported 153 kg N removed in a 12 t/ha maize grain (14% moisture, 1.3%N). Reid et al. (2001a) suggested that a typical 15 t/ha maize crop will have approximately 275 kg N residing in grain at harvest (1.8%N). Thus the grain yields, N uptake and % N in grain are close to the ranges reported in the literature (Steele et al., 1981; Reid et al., 2001a; Reid et al., 2002).

The above ground N accumulation of sweet corn can range between 130 to 240 kg N/ha (Hanly, 2001). Similarly, Reid et al. (2001b) reported that a typical sweet corn crop having 25 t/ha cob yield requires an absorption of about 180 kg N/ha. The amount of N removed in the Manawatu experiment is within this range of reported values. As explained earlier, the amount of N accumulation and redistribution to grain depends not only on the general nutrient N status of soil but also the weather conditions.

In the Manawatu experiment, approximately 44 and 26 % of total N accumulation in maize and sweet corn occurred between 0-80 DAS, 34% (maize) and 42% (sweet corn) total N accumulation between 81 to 110 days, with a further 22% (maize) and 32 % (sweet corn) between 111 to 140 days (which was close to sweet corn maturity stage) (Table 4.11). This shows that N uptake by maize and sweet corn continued throughout the entire growth period, which is in agreement with other studies that have shown that maize accumulates N throughout the growing season (Berger, 1962; Aldrich and Leng, 1969; Ritchie, 1997). Supply of N to plant roots is mostly via mass flow with water uptake. Therefore, there is often a close relationship between N uptake and plant water use as well as the amounts of soil nitrate generated (Greenwood, 1976). This is discussed further in detail in Chapter 6.

There was no significant difference in the total N uptake between P fertiliser treatments for both cultivars in the Manawatu experiment. This was not unexpected as dry matter

yields did not differ significantly between P treatments and, furthermore, the dry summer during that season may have limited the potential of P fertilisers to influence plant N requirement. This lack of P effect was reflected in similar grain N yields for maize between P fertiliser treatments (data not shown).

Table 4.11 The amount and percentage of total N uptake (%) by maize and sweet corn at different growth intervals in the Manawatu experiment.

Cultivars	0-80 DAS	81-110 DAS	111-140 DAS
Maize	44 (79 kg N/ha)	34 (140 kg N/ha)	22 (178 kg N/ha)
Sweet corn	26 (41 kg N/ha)	42 (108 kg N/ha)	32 (161 kg N/ha)

values a e in rows/columns a e mean for th ee P treatments

4.4.4 Plant tissue N concentration

In the Manawatu field experiment, sweet corn had significantly higher N concentration in the leaves at 110 and 140 DAS compared with maize (Table 4.8). Cornforth and Steele (1981) have reported the recommended optimum N concentration of maize leaves in New Zealand to be 2.25–3.30% at crop silking stage (R1). The mean total leaf N concentrations for both cultivars were from 2.5 to 3.4 % at 80 and 110 DAS (approximately silking) showing no N deficiency for either cultivar. However, at sweet corn harvest stage (140 DAS), the values were below the recommended values (Table 4.8). The decrease of N concentration in leaves and stem (with tassel) with time indicates that the larger proportion of N is translocated from vegetative plant parts to the grain, as at maturity about two-thirds of the total plant N is reported to be in the grain (Berger, 1962). These translocation and physiological changes in mature leaves mean that it is unlikely that the lower total leaf N concentrations observed at 140 DAS indicates any N deficiency. However, the possibility that soil N supply may have been limited by dry soil conditions occurring later in the growing season in the Manawatu experiment cannot be discounted. At the final maize harvest (200 DAS), the maize grain N concentration of 2.0% measured in this field experiment was greater than earlier reported values of 1.5% (see review by Reid et al., 2001a and Reid et al., 2002). Kernel N concentrations of sweet corn were not measured.

4.4.5 Nutrient N:P ratios

The nutrient ratio (N:P) can be used as a tool in studies to assess nutrient balance and the crop nutrient status (Cornforth and Steele, 1981). In the Manawatu field experiment, the mean nutrient ratio (N:P) for maize and sweet corn was 12.9, 10.6 and 9.4 for 80, 110 and 140 DAS, respectively. These values are within the range of values for maize grown in New Zealand (Cornforth and Steele, 1981). The nutrient ratio decreased with crop growth by 18 and 27 % at 110 and 140 DAS compared with 80 DAS. This means that the N uptake rate later in the season was lower than P uptake.

4.4.6 Internal P use efficiency

4.4.6.1 Effect of cultivars

Compared with sweet corn, maize had significantly higher internal P use efficiency (E_{PI}) values (kg DM/kg P uptake) at 100 DAS in the Hawke's Bay field experiment (Table 4.3), and throughout the Manawatu experiment (Table 4.6). This indicates that maize was more P efficient (internally) than sweet corn in both field experiments, producing a higher dry matter yield than sweet corn under low soil P status (Chapter 3, Table 3.7 & 3.14). With large experimental errors in total P uptake (11-33 %), it was not possible to prove that maize and sweet corn differed in their external P efficiency (for external P efficiency, see discussion in Chapter 5, section 5.4.5 on P uptake per unit root mass).

When E_{PI} was plotted against thermal time, linear relationships fit well and explained more than 99% variation in E_{PI} for both cultivars (Figure 4.8). These relationships were used to predict when the cultivars started to differ (>10%) in their E_{PI} under different environmental conditions. In the Hawke's Bay experiment, after 600 growing degree days (16 January, 2002), the E_{PI} of maize exceeded that of sweet corn by more than 10%. This indicates that although maize was more P efficient during earlier growth stages, the difference increased with development. In the Manawatu experiment, greater than 10% difference between the cultivars E_{PI} values occurred at 400 growing degree days (8 January, 2003). This indicates that maize was more P efficient than sweet corn under the drier soils in the Manawatu experiment.

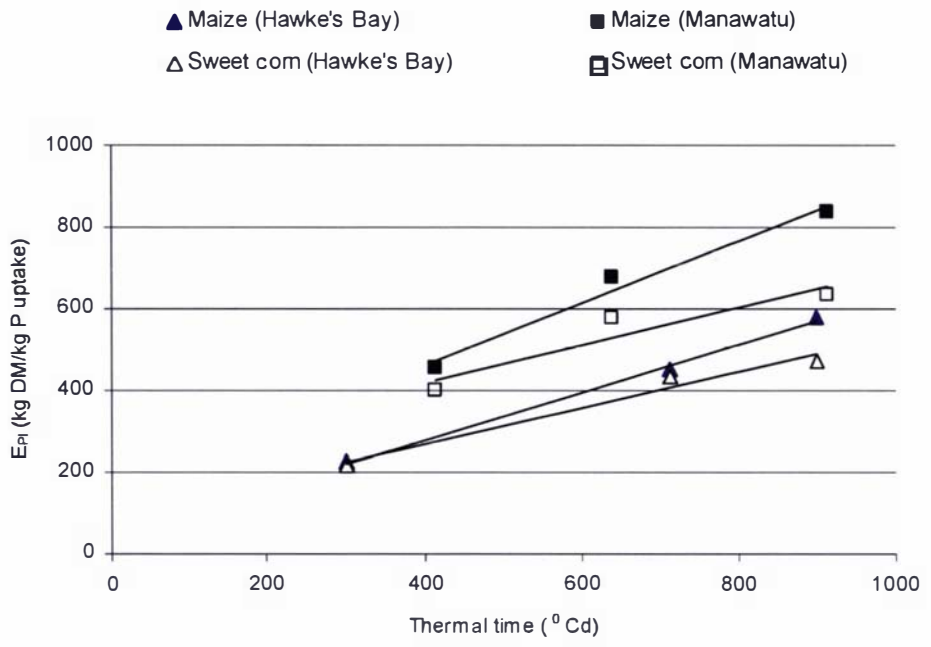


Figure 4.8 The relationship between E_{PI} values (mean 3 P treatments) and accumulated thermal time for maize and sweet corn in the Hawke's Bay and Manawatu experiments; linear fits.

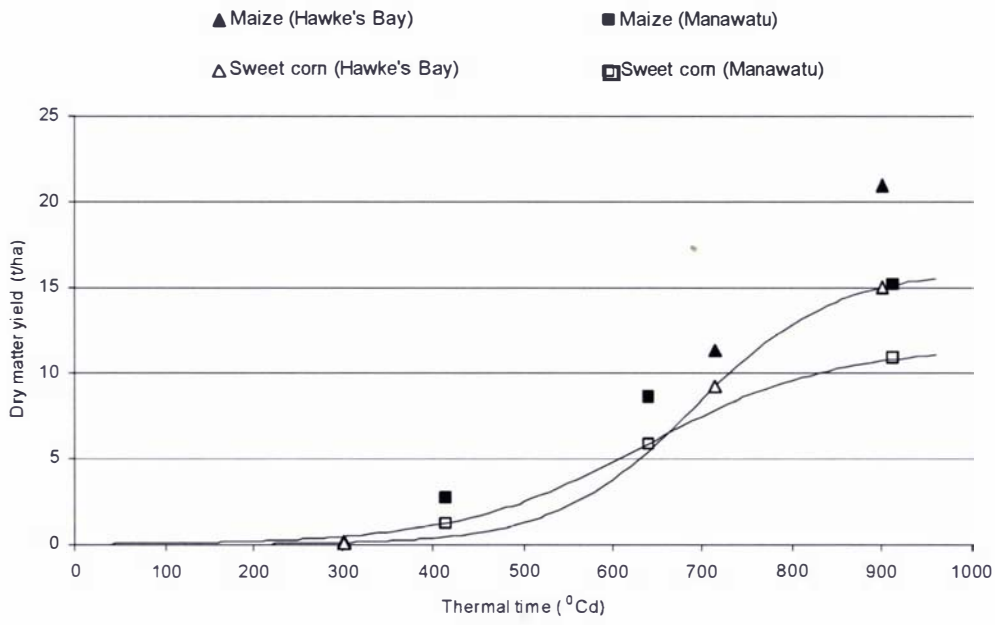


Figure 4.9 The relationship between total dry matter yield (mean P 3 treatments) and accumulated thermal time for both cultivars in the Hawke's Bay and Manawatu experiments; Sigmoid curve fits for sweet corn growth only. Hawke's Bay $Y=16\ (1+6849e^{-0.01277\,t})$ & Manawatu $Y=12\ (1+416e^{-0.00949\,t})$ ($R^2=1$).

The difference between the E_{PI} (mean across P treatments) of cultivars was more noticeable once the maize internal P use efficiency index was greater than approximately 450 kg DM/kg P uptake value (Figure 4.8 and Table 4.3 & 4.6). This is equivalent to a whole shoot P concentration of approximately 0.22%. Table 4.4 shows that the lower P uptake in the Manawatu resulted in higher values of E_{PI} in maize (Figure 4.8), which increased more rapidly than sweet corn between 110 and 140 DAS (Table 4.6). Significant differences in the E_{PI} values (mean across P treatments) between cultivars occurred at R1/R2 growth stage (reproductive) in the Hawke's Bay experiment (100 DAS), but the differences occurred earlier at V7/V8 growth stage (vegetative) in the Manawatu experiment (80 DAS). Figure 4.8 indicates that singly, neither thermal time nor growth stage (which relates to thermal time) caused cultivar or location differences in the E_{PI} values. It seems that these differences are more related to factors controlling soil P supply (e.g. soil water content and soil available P concentration) which are discussed further in section 4.4.6.2 and Chapters 5 & 6).

4.4.6.2 Effect of experiment sites

The E_{PI} values for both cultivars were higher in the Manawatu experiment than in the Hawke's Bay experiment (Figure 4.8). These higher E_{PI} values resulted from a mean reduction in total P uptake that was greater than the reduction in total dry matter yield.

In both field experiments (Hawke's Bay and Manawatu), sigmoidal curves described the relationships between total P uptake and thermal time (Figure 4.7) and total dry matter against thermal time (Figure 4.9) with both cultivars. There were marked differences (>20%) in total plant dry matter produced between locations for both cultivars for the period of thermal time greater than 600 ^{0}Cd (Figure 4.9). For example, between 640-840 ^{0}Cd the total dry matter growth rate for sweet corn (71124 plants/ha) in the Manawatu averaged 0.042 t/ha/ ^{0}Cd, which was only 22% lower than the value of 0.053 t/ha/ ^{0}Cd for sweet corn in the Hawke's Bay. As mentioned in section 4.4.1 for the same period the sweet corn P uptake rates in the Manawatu was 58% lower than in the Hawke's Bay (Figure 4.7) [Maize comparisons are confounded because of the difference in plant population between both sites]. This comparison of the relative changes in total P uptake (Figure 4.7) and dry matter production (Figure 4.9) indicates

that the main driver of high E_{PI} in the Manawatu was a slower P supply. Both sites had similar initial soil P status (Olsen P test values) of 13 and 11 mg P/kg soil in the Hawke's Bay and Manawatu. In the Manawatu experiment, however, the average soil volumetric water content (0-400 mm depth) from 80 DAS onwards was 20% lower than the Hawke's Bay experiment. Lower soil volumetric water content will generate slower P diffusion rates to roots and results in lower P supply (Tinker and Nye, 2000). This influence of soil water on P supply is investigated in more detail in Chapter 6.

Little research is available on measuring phosphorus use efficiency indexes under maize and sweet corn cropping system. Most of New Zealand's maize and sweet corn studies (Steele et al., 1982; Steele, 1985; Munir, 2000; Hansen, 2000; Hanly, 2001; Reid et al., 2002) have reported on measuring P uptake on harvestable product only i.e. grain yield. Therefore, whole crop P use efficiencies have not been considered. Overseas studies to differentiate P efficient plants under low P conditions are often limited to seedling growth stages. In this study (both field experiments), the calculated internal P use efficiency (E_{PI}) values under maize ranged from 226 to 577 in the Hawke's Bay and 454 to 837 in the Manawatu during plant establishment, vegetative and reproductive stages. These E_{PI} values are higher than those reported (163 to 260) for the silking stage of maize grown on a Vertisol soil in sub-humid environment (Sigunga et al., 2002). The lower E_{PI} values reported by Sigunga et al. (2002) could be due to higher soil P status (not reported in their paper) and lower yield potential. In their experiment, maximum maize grain yields ranged between 6.6-6.7 t/ha with plant population of 53000 plants/ha compared to the maize grain yields of 16 t/ha (87119 plants/ha) and 10 t/ha (71124 plants/ha) in the Hawke's Bay and Manawatu experiments.

4.5 Conclusions

The hypothesis set for this Chapter 4 was that maize and sweet corn differ in their amounts of P taken up per hectare. This is not supported by the experimental evidence within the bounds of statistical significance. At the final harvest, maize did not take up more P than sweet corn. However, maize did take up more P in the earlier plant establishment and development stages. At the silking stage, both cultivars had total leaf P concentrations within the range of recommended values for maize crops in NZ (0.18-0.33%), indicating that P deficiency was unlikely. The evidence indicates that only in the later stages of growth in the Manawatu experiment was soil P supply a limiting factor for P uptake.

Maize was more internally P efficient than sweet corn, producing more dry matter per unit of P taken up. Internal P use efficiency (E_{PI}) is a useful index to differentiate cultivar P utilization, but it is more meaningful if considered with external P uptake efficiency (amount of P uptake per unit root dry weight) index for a given crop species. Limitations to P supply in the root zone will initially influence external P efficiency through decreasing the P uptake rate. This may then lead to an increasing internal P use efficiency. In the next Chapter, there is investigation into growth conditions in the Manawatu experiment that lead to rapidly increasing internal P use efficiency values during the later stages of crop growth. External P efficiency is discussed in the next Chapter.

CHAPTER 5

MAIZE AND SWEET CORN ROOT SYSTEMS IN THE HAWKE'S BAY AND MANAWATU FIELD EXPERIMENTS

5.1 Introduction

The overall aim of this Chapter was to test the hypothesis formed in Chapter 2, section 2.9 that maize and sweet corn differ in their root systems (root biomass). In both experiments (Hawke's Bay and Manawatu, Chapters 3 and 4), maize produced significantly more dry matter yield than sweet corn at all sampling stages. Maize also took up more P at the earlier vegetative stages, but by final harvest at 100 DAS (Hawke's Bay) and 140 DAS (Manawatu), the two cultivars had similar total P uptake. One reason for the differences in P uptake between cultivars in the early growth stages could be the extent and morphology of the root systems. It has been recognised that ability of root systems in particular root length generated per unit volume of soil to explore fertilised soil horizons in nutrient acquisition (Barber, 1984; Wiesler and Horst, 1994) is one of the most important factors to improve the acquisition of soil phosphate (Tinker and Nye, 2000).

Research studies have shown that a rapidly established root system is critical for early P uptake in maize because P is relatively unavailable and immobile in many soils (Silberbush and Barber, 1983; Barber, 1984). Unlike N, P supply in soil is dependent upon diffusion over millimetre distances rather than mass flow over centimetres (Nye and Tinker, 1977; Barber, 1984; Tinker and Nye, 2000). Clark (1983) reported that there is significant genetic variation in P uptake, accumulation and use in maize, which could be expected to be reflected in root mass and morphology. The extent of P uptake is dependent on root number, length, diameter and surface area in contact with the soil (Schenk and Barber, 1979; Anghinoni and Barber, 1980; Zhang and Barber, 1992). Efficient P uptake by plants is enhanced by root characteristics such as long roots resulting in a large root surface per unit of shoot (Schenk and Barber, 1979, 1980; Lynch and Brown, 2001). Small root diameter and especially long root hairs improve the acquisition of P from soil (Barber, 1995; Jungk, 2001; Trolove et al., 2003).

The ability of a genotype to increase root surface area in response to soil P levels could help to support high rates of P uptake during early stages of growth. Extension of the root system deep into the soil profile may remove P constraint to growth, if the lower layers of soil are able to supply plant available P.

In this Chapter, the root systems of maize and sweet corn are measured in an attempt to explain the maize and sweet corn yields, P uptake and phosphorus use efficiency observed in earlier Chapters. Extensive P efficient root systems may explain why maize and sweet corn did not exhibit growth responses to fertiliser P applied at the Hawke's Bay and Manawatu experiment sites (Chapters 3 & 4).

The study of roots under natural field conditions is technically difficult. No standardized methods exist (Chapter 2, section 2.7). Furthermore, most root measurement techniques are time consuming and often inaccurate (Bohm, 1976; 1979). Some root studies are based on coring soils to depths followed by washing roots from the sectioned cores. These methods are often reliable but also very time-consuming (for detail see Chapter 2, section 2.7.2).

In this chapter, the profile-wall technique (Bohm, 1976, 1979) was used to obtain quantitative data about the distribution of maize and sweet corn roots as influenced by soil phosphate status in the Hawke's Bay field experiment. For comparison, a soil coring technique was also used and evaluated. Two root corers (for soft and hard soil conditions) were developed, tested and used to measure maize and sweet corn root growth and the depth of root systems under Manawatu sandy loam soil conditions (Aslam, 2003).

5.2 Materials and Methods

5.2.1 Root sampling techniques and dates

In the Hawke's Bay field experiment (2001-02), during crop growth period from 14 November 2001 to 15 May 2002, two root measuring techniques were used. The profile wall measurements (section 5.2.2) were taken on 21.12.2001 (37 DAS), 21.1.2002 (67 DAS) and 26.2.2002 (100 DAS). These measurements were made to assess the size, growth and development of the root systems of both cultivars at crop establishment, rapid vegetative growth and maturity stages.

At 100 DAS (Hawke's Bay), the soil coring technique (Matthew, 1992) (Matthew's root corer, 62.5 mm diameter) was used to take soil root samples within the 0-400 mm soil depth from three different locations around single plants in each replicate as explained by Anderson (1988). Anderson (1988) used a 76 mm diameter steel tube corer to estimate the size of field grown maize root system in USA. In this experiment, the root samples were collected from three locations; L_0 (vertical positions below the plant stem), L_1 and L_2 (vertical positions below the soil surface at 150 and 300 mm in row) as shown in Plate 5.1. Soil core samples collected from each location were divided into four depths (0-100, 100-200, 200-300 and 300-400 mm) to examine the quantity of roots in each depth (Plate 5.2).

In the Manawatu field experiment (2002-03), during the crop growth period from 22 October 2002 to 15 May 2003, three different techniques were used to obtain quantitative data on root systems and distribution for both cultivars. At 50 DAS, when maize and sweet corn plants were around 30 cm high, one full plant from each replicate of the main P fertiliser treatments (0, 15 and 70 kg P/ha) was excavated carefully with hands and spade for root examination.

At 80 (establishment), 110 (rapid vegetative growth) and 140 (maturity) DAS, the root samples were taken using Aslam's root corer (50 mm diameter) as explained in section 5.2.3.2. The soil cores were taken from three locations (L_0, L_1, L_2) and divided into four depths as explained above for Hawke's Bay experiment at 100 DAS (Plate 5.1 and 5.2).

At 150 DAS, a trench was used to measure the maximum rooting depth, root interaction between plants and rows, and to draw a natural root sketch of both cultivars. For this

Plate 5.1 Soil sample locations for roots under maize plant at 80 DAS in Manawatu.

Plate 5.2 Cores pushed onto the flat tray to divide into 4 soil depths in Hawke's Bay.

purpose, a 3 m long and 1 m deep trench was dug by backhoe across the rows of the maize and sweet corn control plots 27 and 29, respectively. The face of the trench profile was prepared with a spade and smoothed with the wooden block. A further layer of 2-5 cm thick soil was carefully removed by scalpel and knife to expose the roots. From the base of trench, Aslam's root corer was used to penetrate a further 80 cm deep to measure the maximum rooting depth of maize and sweet corn.

5.2.2 Profile Wall technique

The profile wall technique (Bohm, 1976; 1979) was used with some modifications to obtain quantitative root counts numbers. The following procedures were involved.

5.2.2.1 Digging the pits and preparation of profile wall

Pits 70 cm long (perpendicular to plant row), 50 cm wide and 45 cm deep were dug about 8 cm away from maize and sweet corn plants to observe the root distribution in the soil profile (Plate 5.3). The final vertical working face of the profile wall was prepared with a spade and planed with a wood block. The roots were exposed by using a small scraper and a soft nylon brush. Approximately 2 cm of loose soil from the profile face was removed to expose the roots.

5.2.2.2 Exposing and counting the roots

Root counting started immediately after exposing roots. A metal frame of (60 x 60 cm), with inner square grids (5 x 5 cm) and a spirit-level fixed at the top was placed against the prepared profile wall. The number of exposed visible roots (large, medium, small) in every grid of the frame were counted and recorded (Plate 5.4). New pits were dug around fresh plants for each observation.

Plate 5.3 Maize roots exposed in 70 x 50 cm pit in field at 37 DAS in Hawke's Bay.

Plate 5.4 Root counting by profile wall technique in field at 37 DAS in Hawke's Bay.

5.2.3 Soil coring technique

5.2.3.1 Application of Matthew's developed root corer

A soil corer or sampler was developed by Matthew (1992) at Massey University to measure the pasture root system under New Zealand soil conditions. This was used to measure maize and sweet corn root system in the Hawke's Bay experiment. The corer consisted of a hollow steel tube 1500 mm long having a 62.5 mm inner diameter with a sharp cutting edge at one end. At the other end of the tube, the corer was provided with a big driving hammer (20 kg) which made it possible to drive it into the soil (Plate 5.5). Some modification and development of soil root corer was later carried out (see below).

To take soil plus root samples, the corer was driven to reach the desired depth. Small side ways movements were used to break contact between the corer and the soil before it was manually withdrawn. The sample filled tube was turned upside down and the cores pushed out using a wooden dowel onto the flat trays as shown in Plate 5.2. The intact soil cores were divided into four segments (0-100, 100-200, 200-300 and 300-400 mm). The whole procedure was repeated in each replicate plot and treatment. After collection, soil cores were stored in airtight plastic bags at 6 ^{0}C till they were processed. The open holes from which the samples were taken were refilled with the soil available at the surface.

5.2.3.2 Modification and development of root corer

For the Manawatu experiment, two soil root corers (Aslam's root corer) were developed at the Agricultural Engineering Workshop, Massey University, Palmerston North (Plate 5.6). The intact corer for dry soil conditions consisted of a stainless steel cylindrical tube 1200 mm long with 50 mm inner diameter. The penetrating end of the corer was welded with a sharp cutting tip of 45 mm diameter and the other end was provided with a 9 kg driving hammer to drive it into the soil. For soft moist soil conditions, another corer with the same specifications was developed. The penetrating end of this corer was sharpened stainless steel without any hardened cutting tip and the other end was fixed with a ratchet driven plunger to extrude the sample (Plate 5.6). To take soil plus root samples, the procedure in section 5.2.3.1 was repeated.

Plate 5.5 Matthew's root corer driven by driving hammer in Hawke's Bay field.

Plate 5.6 Soil root corers developed at Massey (Aslam's root corers) and used for root sampling in Manawatu a) for dry soil condition and b) for soft soil condition.

5.2.3.3 Root washing and drying

For the Hawke's Bay root samples collected by soil coring technique (100 DAS), the root washing was done using a hydro-pneumatic elutriation system (root washing machine) as described by Smucker et al. (1982), which was redesigned and developed by Matthew (1992) at Massey University (Plate 5.7). The washed root samples were oven dried at 70^0C for 72 hours to measure dry root weights from each sample as explained in section 5.2.3.4.

For the Manawatu field experiment, a few soil root samples were washed by using a hydro-pneumatic elutriation system (root washing machine) installed at Massey University by the procedure explained above. A lack of water pressure at the site where this machine was installed for this experiment increased the time consumed to process a sample, and made it necessary to develop a manual root washing technique to process many of the soil root samples (Plate 5.8). The manual technique involved filling a sink tank with water. Then soil root samples were spread over a 1 mm brass, or stainless steel sieve under water, and washed gently by hand. The washed root samples were picked up using tweezers and stored in plastic bag at 6 ^{0}C till fresh weight and root length were determined. Sub samples of the washed root were weighed and taken for root length measurements. After root length was measured, the sub samples and the remaining wet roots were oven dried at 70 ^{0}C for 72 hours to determine root dry weight.

5.2.3.4 Root length and root dry weight

Root length was measured manually by using a modification of the line-intersection method (Newman, 1966; Marsh, 1971; Tennant, 1975). Sub samples of fresh root were weighed and placed in a glass-bottomed tray with enough water to allow the roots to float freely. The tray was placed over a grid comprised of 1 cm-squares, and the roots were gently teased apart using tweezers. The number of vertical and horizontal intersections between the roots and the gridlines were counted and the total length of the fresh sub samples was calculated using following Tennant's equation.

$$L = 0.79\ N\ S_G \qquad \text{(equation 5.1)}$$

Plate 5.7 Root washing by hydro-pneumatic elutriation system at Massey University.

Plate. 5.8 Root washing by filling a sink tank water at PTC Massey University.

where; L= total length of the root samples (cm), N = number of root-line intersections, and S_G = grid spacing (cm), which was 1. Total root length was calculated by multiplying the root length sub sample to the total fresh root weight at each soil core section. Root length density (R_v) was calculated for each sample by simply dividing root length by core volume. To calculate the total root length per plant or root length per unit ground area (L/cm^2), the samples taken at 12 positions (3 soil cores and 4 depths) in each core were summed as shown in Figure 5.1.

In order to estimate the size of the field grown root system (maize and sweet corn) from the soil core samples, the following equation was used to provide the estimated root dry weight (M_v) at 0-400 mm on hectare basis.

$$M_v \text{ (kg/ha)} = [(M_v \times A_P)/A_C] \times \text{plants/ha} \qquad \text{(equation 5.2)}$$

where M_v = total root dry weights at 12 positions (3 cores and 4 depths/core); A_P = area under plant (1400 cm^2); and A_C = total area three cores (59 cm^2).

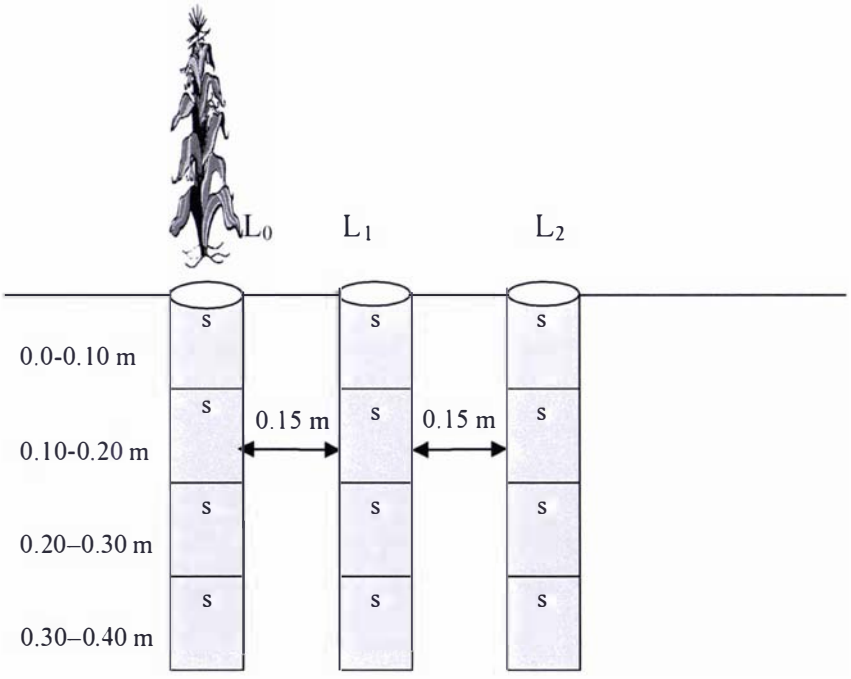


Figure 5.1 The 12 root sampling positions (s) in 3 soil cores (L_0, L_1, L_2) below plants and adjacent to maize and sweet corn plants (as shown in the Plate 5.1).

5.2.4 Soil Penetration resistance measurements

In the Manawatu experiment, after maize harvest (200 DAS), a digital cone penetrometer operated by John Dando of Landcare Research, Palmerston North was used to measure the penetration resistance of the soil (Plate 5.9). The diameter of the 30 degree cone was 1.6 cm with the area of 2 cm^2. A distance of 1500 mm in width and 600 mm depth was used to penetrate the probes as it covered 2 plants between the rows.

Plate 5.9 Digital cone penetrometer measuring soil strength at 200 DAS (Manawatu).

5.2.5 Mycorrhiza infection analysis

In the Manawatu experiment (170 DAS), fresh root samples from 0-100 mm depth were collected from 2 replicates of 0 and 70 kg P/ha treatments for maize and sweet corn. These root samples were washed over a fine sieve to remove soil particles and were separated into four classes (>5, 2-5, 1-2 and <1 mm). Samples of 1 and <1 mm thick roots were selected and kept in cold storage (<5 ^{0}C) for one week prior to assessing the mycorrhizal infection.

The root samples were subjected to a staining procedure modified from Koske and Gemma (1989). Each sample of 1g was rinsed in de-ionised water, placed in a test tube containing 20 ml of a 2.5% aqueous solution of KOH (w/v), heated in a water bath at 80-90 ^{0}C for 30 minutes, and then transferred to 20 ml of a 1 % HCl solution. A staining solution was made by mixing 200 ml of glycerol with 180 ml of water and 20 ml of 1% HCl; 0.1 g of Trypan Blue powder was then placed in 10 ml of water, brought to boiling, and passed through a Whatmans 41 filter into 200 ml of the acidic glycerol solution. The root samples were removed from the acid after 24 hours, placed in tubes containg in 20 ml of the staining solution, and heated in a water bath at 90 ^{0}C for 30 minutes. Samples were stored in the dark for 24 hours in 20 ml of acidic glycerol solution to remove excess stain, before being mounted on slides for viewing with a light microscope. The presence or absence of arbuscules in 10-15 mm sections of root sample was recorded.

5.2.6 Statistical analyses

Statistical analyses were performed using the General Linear Model (GLM) software of the Statistical Analysis System (SAS Institute, 1999-2001). Data were analysed by Analysis of Variance (ANOVA) for a 2 x 3 factorial arrangement. Least significant differences (LSD) at 5% were used to detect differences (among means) between cultivars and P fertiliser treatments at different sampling stages.

5.3 Results

5.3.1 Hawke's Bay field experiment season 2001-02

5.3.1.1 Root count numbers (by Profile wall technique)

With both cultivars, root count numbers increased rapidly with time after emergence. At 37, 67 and 100 DAS, the total root count numbers under maize were 27, 31 and 19% greater (P=0.05) than under sweet corn (Table 5.1). However, no significant differences (P=0.05) were found in the root count numbers between P fertiliser treatments within a cultivar at any sampling time. There were significant differences in root count numbers between different depths. On average, topsoil depths had higher root count numbers than lower soil depths. A graphical illustration of the depth trends is given in Figures 5.2 and 5.3.

Table 5.1 Summary of total root count numbers under maize and sweet corn at various crop growth stages during 2001-02 season in the Hawke's Bay.

Treatments (kg P/ha)	Root count numbers (within 600 x 600 mm grid area)					
	37 DAS		67 DAS		100 DAS	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	140 a	110 a	514 a	384 a	981 a	710 a
100	150 a	118 a	563 a	458 a	878 a	682 a
200	144 a	116 a	681 a	497 a	762 a	817 a
Mean	145 a	115 b	586 a	447 b	874 a	736 b
LSD (0.05)	17		77		103	
Significance						
cultivar	s		s		s	
fertiliser	ns		ns		ns	

Means values in row (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

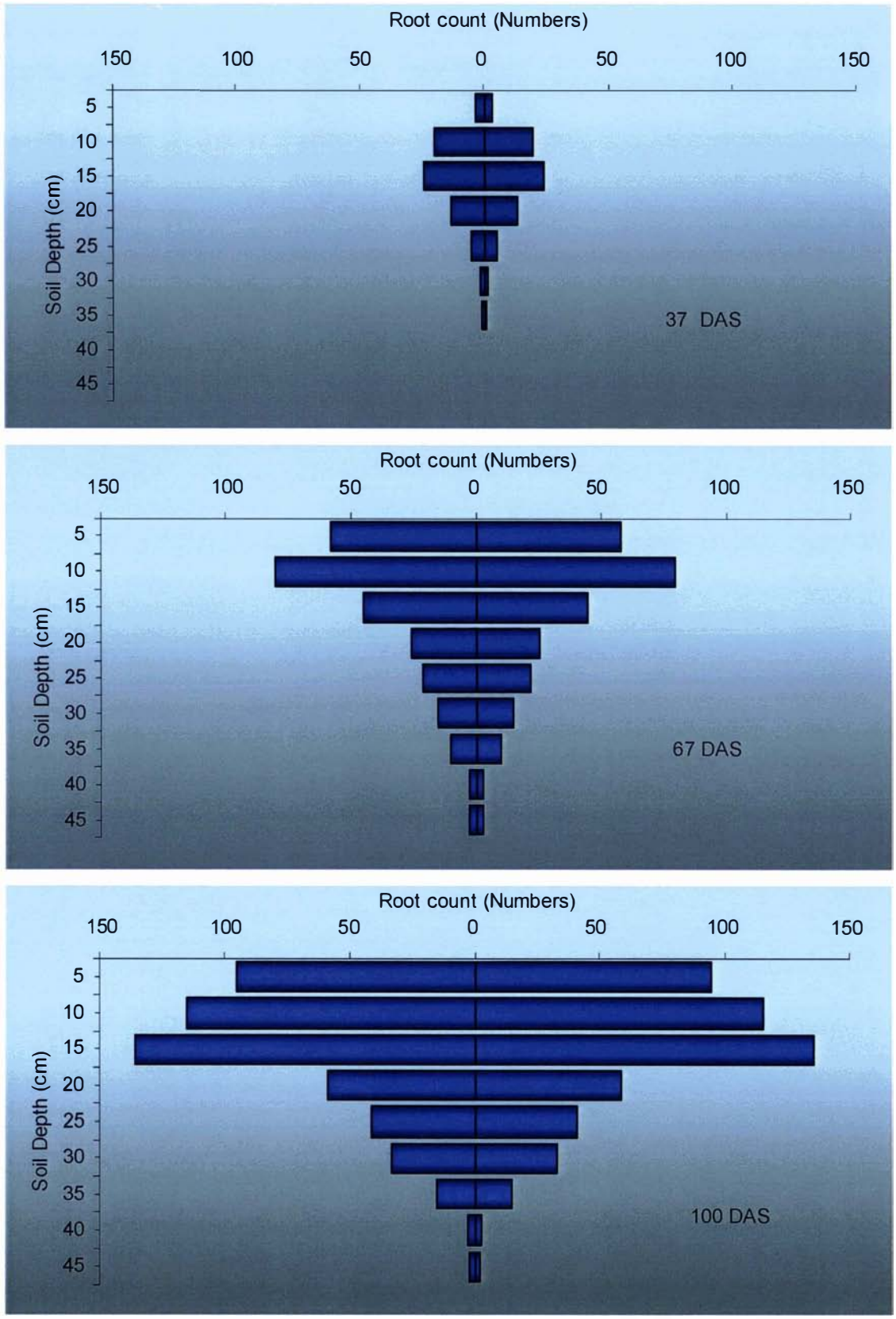


Figure 5.2 Root distribution for maize (control treatment) at 37, 67 and 100 DAS during the 2001-02 season at Hawke's Bay (by profile wall technique).

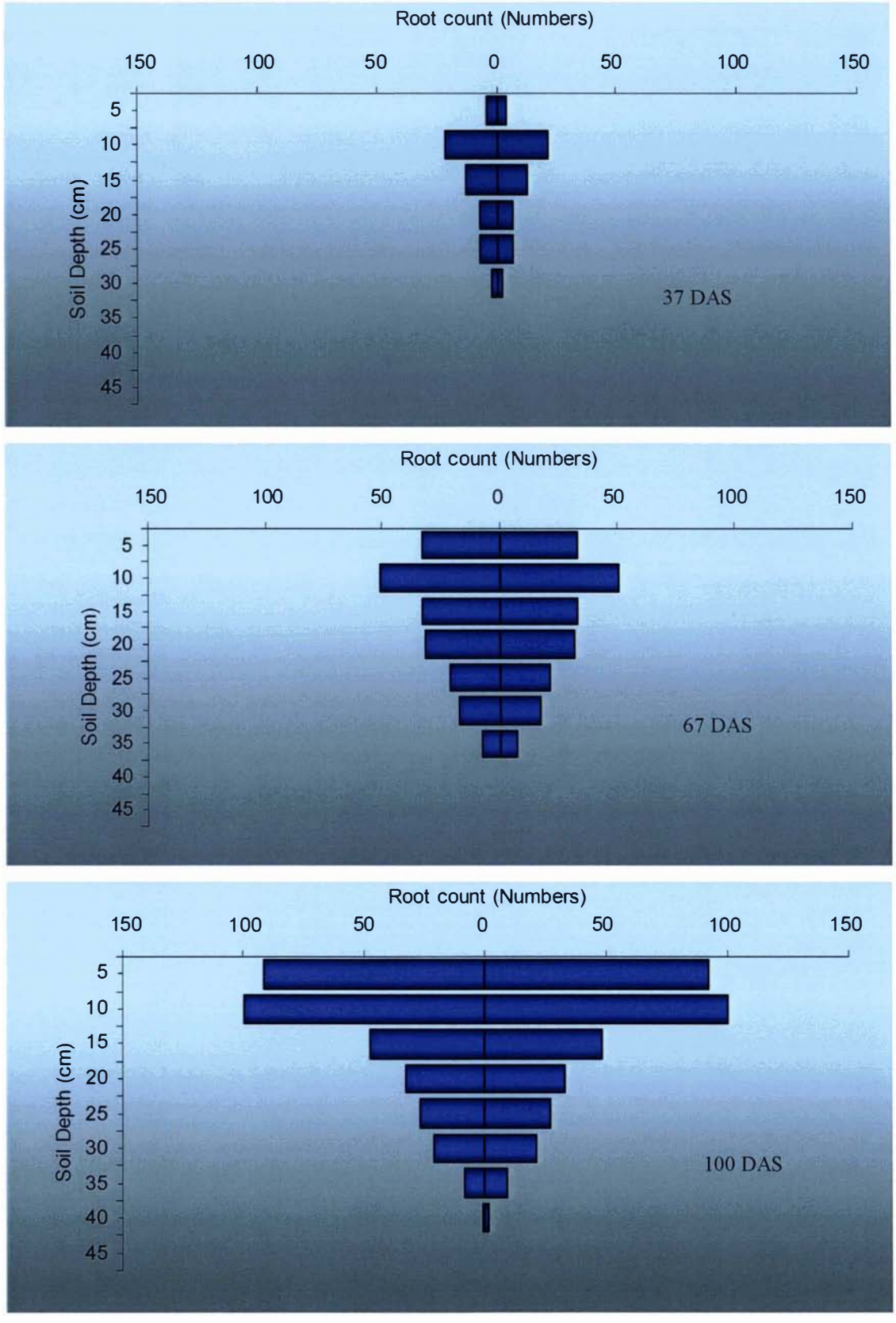


Figure 5.3 Root distribution for sweet corn (control treatment) at 37, 67 and 100 DAS during the 2001-02 season at Hawke's Bay (by profile wall technique).

5.3.1.2 Root dry weights (by soil coring technique)

At 100 DAS, the estimated root dry weight (mean across all P treatments) in the 0-400 mm root zone (total 4 depths & 3 locations) for maize was significantly higher ($P<0.05$) than for sweet corn (Table 5.2). This shows that maize had 3 times greater root dry weights than sweet corn. There were no significant differences in below ground root dry weights between P fertiliser treatments in sweet corn. In contrast, with maize, the control treatment had 24% more root weight than the 200 kg P/ha treatment (Table 5.2).

Estimated root dry weights and the measured plant dry matter yield obtained at 100 DAS (Chapter 3) were used to calculate root:shoot ratios for the maize and sweet corn. The mean (across all P treatments) above ground plant dry matter yield for maize and sweet corn were 20970 and 14667 kg DM/ha produced at that stage (100 DAS) (Chapter 3, Table 3.7). The root:shoot ratio for maize (0.13) was double that of sweet corn (0.06) at that stage (100 DAS).

Table 5.2 Estimated root dry weight for maize and sweet corn in the Hawke's Bay field experiment at 100 DAS (0-400 mm depth) (2001-02).

Treatments (kg P/ha)	Estimated root dry weight (kg/ha) at 0-400 mm	
	Maize	Sweet corn
0	3332 a	973 a
100	2643 ab	901 a
200	2128 b	858 a
Mean	2701 a	911 b
LSD (0.05)	503	
Significance		
cultivar	s	
fertiliser	ns	

Means values in row (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

5.3.2 Manawatu field experiment season 2002-03

5.3.2.1 Root dry weight at 50 DAS (by excavation technique)

At 50 DAS, the root dry weights (mean for three P treatments) for maize and sweet corn were 27 and 10 kg/ha respectively, a relative difference of 170 % (Chapter 3, Table 3.13). At that stage, maize also had significantly longer root length than sweet corn (Chapter 2, Plate 2.3). The root:shoot ratio for maize and sweet corn were found to be 0.36 and 0.24, respectively (Chapter 3, Table 3.13).

5.3.2.2 Root dry weights at 80, 110 and 140 DAS (by soil coring technique)

At 80, 110 and 140 DAS, the total estimated root dry weights (mean across all P treatments) in the 0-400 mm root zone (total for 4 depths & 3 locations) for maize were 62, 87 and 44 % greater than to sweet corn (Table 5.3). However, no significant differences (P=0.05) were found between the P fertiliser treatments within a cultivar at any sampling time. For both cultivars, at all sampling times there were significant differences between depths and width (locations) in terms of root dry weight.

Table 5.3 Maize and sweet corn root dry weight (kg/ha) at 80, 110 and 140 DAS in the Manawatu experiment (season 2002-03).

Treatments	Total relative root dry weight (kg/ha) at 0-400 mm soil depth					
	80 DAS		110 DAS		140 DAS	
Prate (kg/ha)	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	436 a	236 a	2653 a	1129 a	3005 a	1817 a
15	308 a	203 a	2376 a	1512 a	2070 a	1729 a
70	341 a	228 a	2524 a	1394 a	2504 a	1726 a
Mean	362 a	223 b	2518 a	1345 b	2526 a	1758 b
LSD (0.05)	109		564		603	
Significance						
cultivar	s		s		s	
fertiliser	ns		ns		ns	

Means values in row (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

5.3.2.3 Root length density at 80, 110 and 140 DAS (by soil coring technique)

At 80, 110 and 140 DAS, the root length density (mean across all P treatments) in the 0-400 mm root zone (total for 4 depths & 3 locations) for maize were 75, 22 and 34 % higher compared to sweet corn during those sampling periods (Table 5.4). At 80 DAS, there were no significant differences (P=0.05) in the root length density between the P fertiliser treatments within a cultivar. However, some differences between P fertiliser treatments were observed with both cultivars at 110 & 140 DAS. As for root mass, significant differences were found in the root length density for depths and width (locations) under both cultivars thoughout sampling period.

Table 5.4 Maize and sweet corn root length density (cm/cm^3) at 80, 110 and 140 DAS in the Manawatu experiment (season 2002-03).

Treatments	Root length density (cm/cm^3) at 0-400 mm soil depth					
	80 DAS		110 DAS		140 DAS	
Prate (kg/ha)	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	1.63 a	0.74 a	3.95 a	2.88 a	4.41 a	3.41 a
15	1.48 a	0.93 a	2.83 b	2.14 b	3.14 b	2.33 b
70	1.52 a	0.97 a	3.29 ab	3.14 a	3.41 ab	2.40 b
Mean	1.54 a	0.88 b	3.36 a	2.75 b	3.65 a	2.73 b
LSD (0.05)	0.29		0.47		0.44	
Significance						
cultivar	s		s		s	
fertiliser	ns		s		s	

Means values in row (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)
LSD is for cultivars

5.3.2.4 Maize and sweet corn maximum rooting depth

At 150 DAS, the maximum rooting depths for maize and sweet corn were found to be 1.5 and 1.0 metres under the Manawatu fine sandy loam soil. For the maize control treatment, each observation on the three replicate found roots going down to 1.5 m, whereas only one replicate from sweet corn control found roots going down to 1.0 m.

It was also observed that the maize had thicker roots and roots overlapping between plants/rows. By contrast, the sweet corn roots were thinner and less overlapping within plants/rows. The overall root structure for both cultivars were similar. For example, the brace roots close to the stem were found in a clustered form with both cultivars. Figure 5.4 shows the root structure sketch drawn by hand in the field for both cultivars.

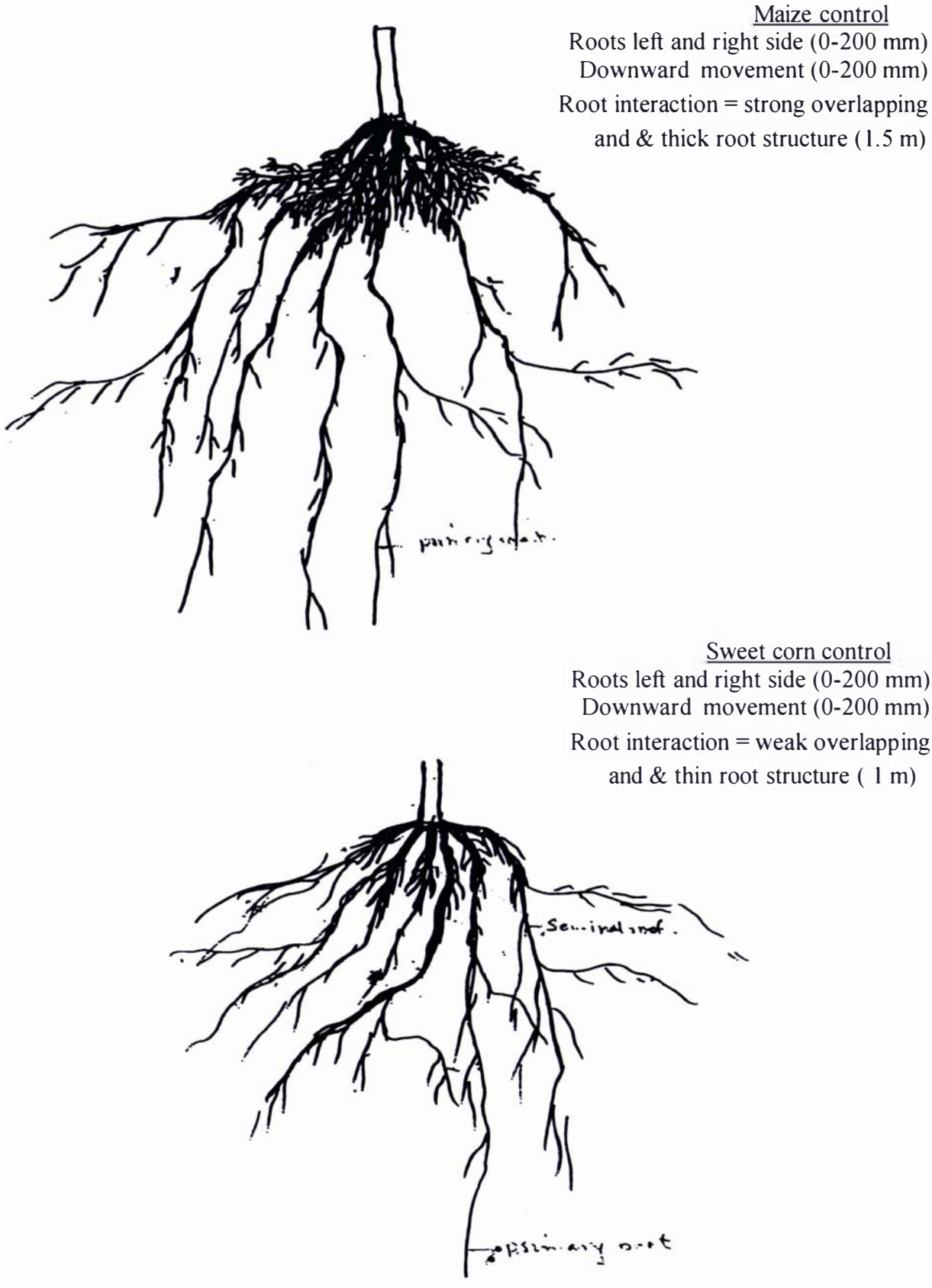


Figure 5.4 Hand drawn maize and sweet corn mature root system under Manawatu sandy loam soil at 150 DAS.

5.3.2.5 Soil penetration resistance

Significant differences ($P<0.0001$) were found in penetration resistance values between the soil depths. The topsoil layers (0-100 and 100-200 mm) had lower values than lower soil depths (Table 5.5).

Table 5.5 Soil penetration resistance (MPa) under maize and sweet corn control plots in the Manawatu experiment site (season 2002-03).

Soil depth (mm)	Soil penetration Resistance (MPa)		
	Maize	Sweet corn	Mean
0-100	0.48	0.47	0.48 d
100-200	0.64	0.57	0.61 d
200-300	1.22	1.18	1.20 c
300-400	1.46	1.59	1.52 bc
400-500	1.60	1.62	1.61 b
500-600	1.90	2.23	2.06 a
Mean	1.21 a	1.28 a	
Significance depth	s		s

Means values in row and columns (depths) followed by same letter show no significant differences (P=0.05)

In Figure 5.5, a colour scale is used to represent soil penetration resistance (MPa) in topsoil profile along one single transect between horizontal and vertical soil profile. This gives a clear impression of the variability found (0-200 mm). Some dark red spots in the bottom layer at 600 mm indicate a maximum pressure >3 MPa which could restrict root growths at that soil depth (Leonard, 2001).

Horizontal and vertical root count data obtained using the profile wall technique was used to represent location and frequency of maize and sweet corn roots relative to the soil penetration resistance as shown in the Figure 5.5. The horizontal and vertical root mapping shows that root numbers were higher in the topsoil layer (0-200 mm) than the bottom soil layers i.e. most roots were located in the zone of low penetration resistance.

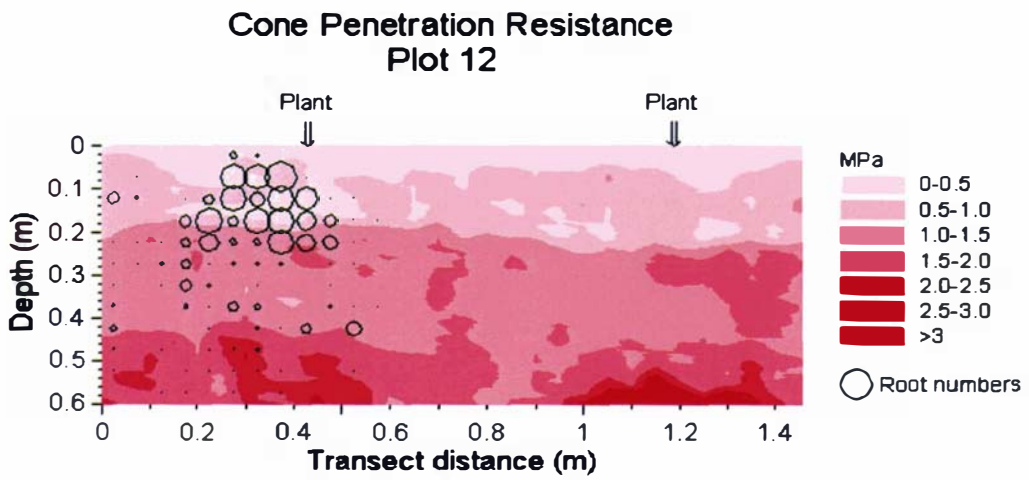


Figure 5.5 Soil profile showing range of soil strength with root numbers under maize in the Manawatu experiment. Circles represent relative root count numbers measured around single plant.

5.3.2.6 Mycorrhiza infection

At 170 DAS, the staining of fine roots showed that roots of both cultivars were infected with VA mycorrhiza (Plate 5.10 and 5.11). The infection was clear and well developed with hyphae, formation of vesicles, arbuscules and even some spores. However, no differences were noted in the proportion of mycorrhiza infection between control and 70 kg P/ha fertiliser treatment.

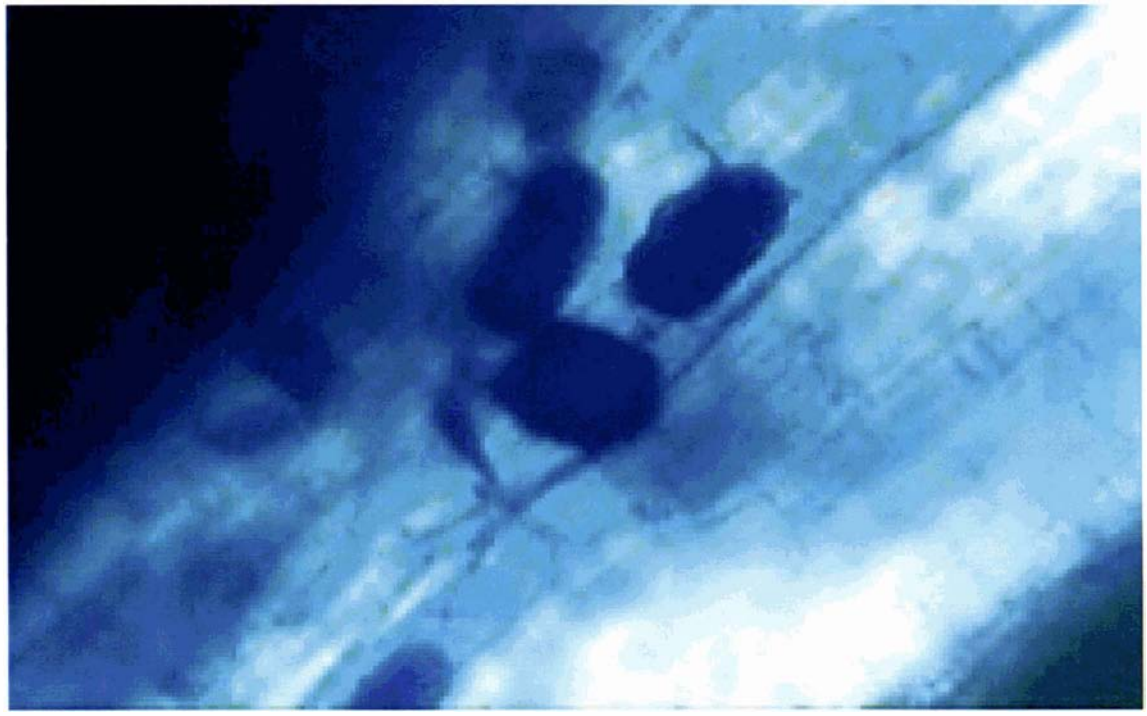


Plate 5.10 Maize root infected by VAM containing mycorrhizal vesicles. (Mag.350x)

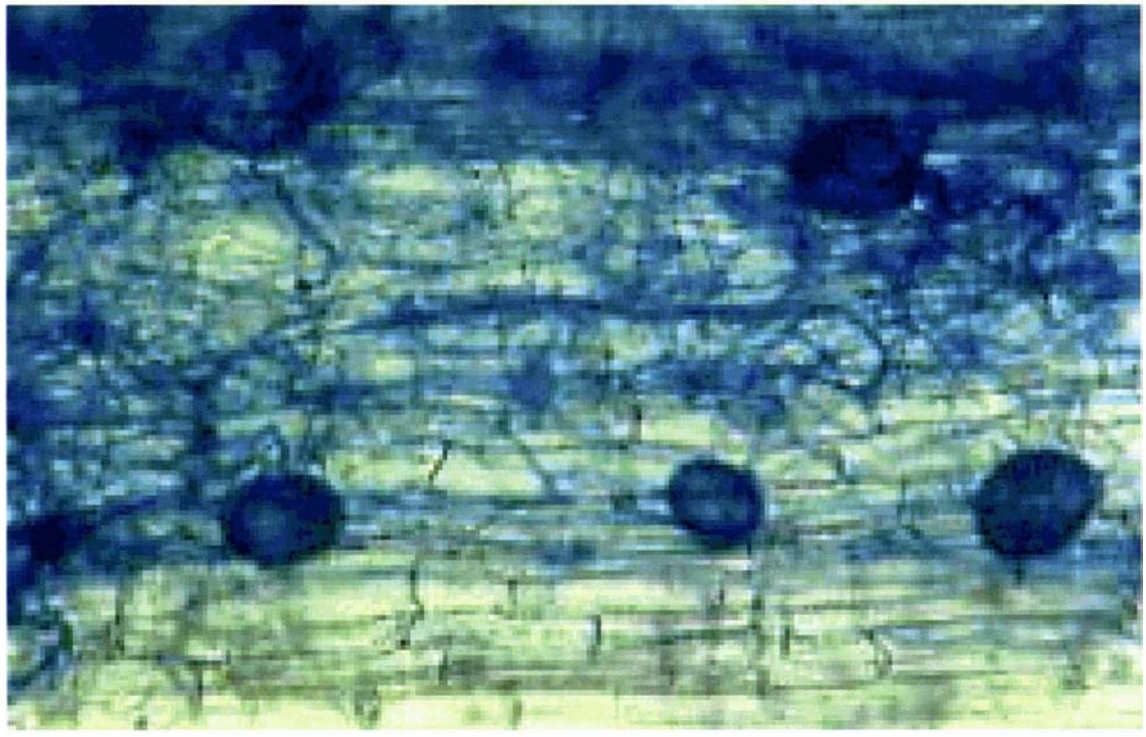


Plate 5.11 Sweet corn root infected by VAM containing mycorrhizal vesicles. (Mag.350x)

5.4 Discussion

5.4.1 Comparison of root measuring techniques

At the outset of this investigation, there was uncertainty surrounding which root measuring technique would be best suited to quantify the maize and sweet corn root systems. Two techniques, the profile wall and soil coring methods were used in the initial field experiment at Hawke's Bay and after comparison of the results from these techniques, two soil root corers (soft and hard soil conditions) were developed to measure the root systems of both cultivars in the Manawatu experiment as explained in section 5.2.1. The comparison of results with advantages and disadvantages of the techniques used are discussed below.

In the Hawke's Bay field experiment, the profile wall technique counted all visible root numbers below the plants within the range of a 600 mm wide x 600 mm deep grid at 37, 67 and 100 DAS. The root count numbers were not measured after 100 DAS because literature and observations indicated that the root system would have reached its maximum extent. In both the cultivars, the root count numbers increased linearly with time during three sampling stages (Figure 5.6). The development of the root system of both maize and sweet corn as assessed by root counts were linearly related to the development of shoot biomass (Figure 5.7).

Bohm (1976) reported similar results, in which the estimated total root count numbers (0-1000 mm soil depth) for maize increased linearly with time when measured at 50, 66 and 88 days after planting. However, in the Hawke's Bay experiment, the total root count numbers of 874 (100 DAS) in the 0-500 mm soil depth under maize (Table 5.1) were lower than those reported by Bohm (1976) for maize root systems (0-1000 mm soil depth) of 2390 at 88 DAS. These root count numbers are only an approximation of the root system in a defined soil volume. These differences probably occurred because of different counting procedures used during the two experiments. For example, Bohm (1976) counted the total number of maize roots expressed (1 root = 5 mm root length) in a profile wall of 1000 mm depth, whereas, in the Hawke's Bay experiment, all the visible roots (profile face) were counted below the plant within the range of 600 mm wide x 600 mm deep grid. Therefore, such variation in reporting root count numbers

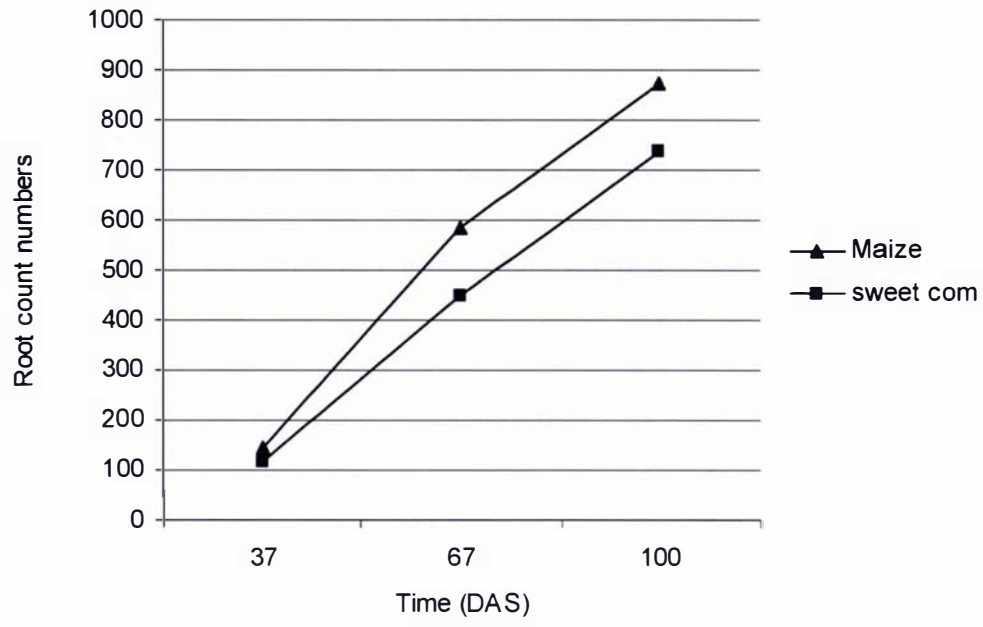


Figure 5.6 Maize and sweet corn total root count numbers at 0-500 mm depth at 37, 67 and 100 DAS in the Hawke's Bay. Results are presented as mean of the 3 P treatments.

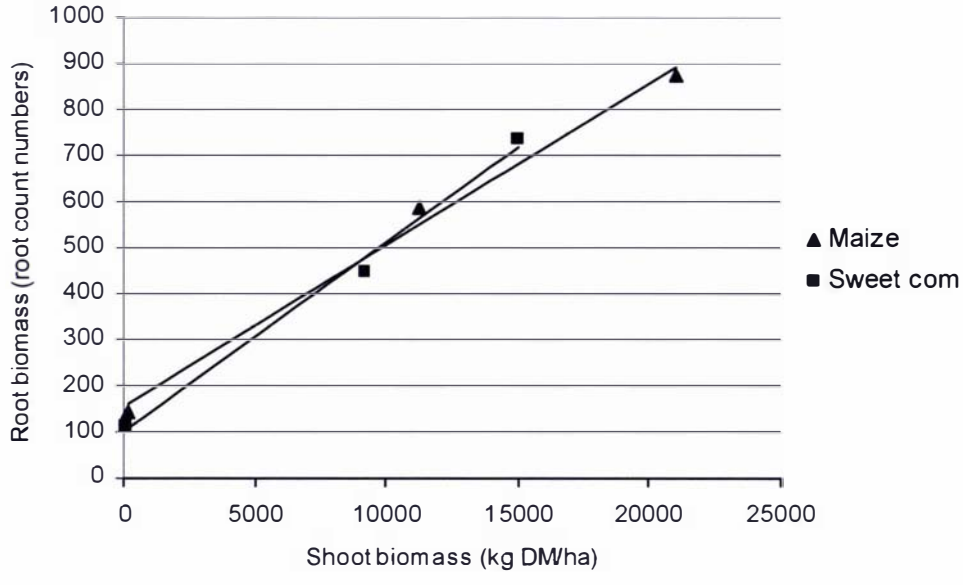


Figure 5.7 Relationship between shoot and root biomass at 37, 67 and 100 DAS in the Hawke's Bay. Results are presented as mean of the 3 P treatments.

could be from the size of the root profile counted under two different sites. In contrast, the total root dry weight values measured by soil coring (Matthew's root corer) at 100 DAS in the same experiment (Hawke's Bay) were comparable (see discussion below) with the reported root dry weight values of a USA study (Anderson, 1988). As there was only one sampling date for soil coring compared to three sampling dates for the profile wall, no relationship could be produced between root count numbers and root dry weights. Both techniques (profile wall and soil coring) confirmed the greater root mass of maize in the Hawke's Bay experiment.

The calculated root dry weights measured by the soil coring technique (Matthew's root corer) provided estimated values of 31 g/plant (0-400 mm soil profile) at 100 DAS in the Hawke's Bay experiment, which was similar to the value (39 g/plant) at 88 DAS in 0-600 mm soil depth of a silt loam soil in a USA (Clarksville) study (Anderson, 1988). In the Manawatu field experiment, the calculated root dry weight measured by soil coring (Aslam's root corer), provided an estimation of total root dry weight of 2518 kg root DM/ha (35 g/plant) at 110 DAS in the 0-400 mm soil depth under maize (Table 5.3), which was consistent with the reported total maize root dry weight of 2418 kg root DM/ha (39 g/plant) at 88 DAS (Anderson, 1988). The root weights obtained suggests that the soil coring technique used to estimate the size of the maize root system allows a consistent comparison with other studies using similar coring techniques such as that of Anderson (1988). The profile wall root counting technique appears to be more operator dependent.

Experience gained during the root sampling measurements by using profile wall (Bohm, 1976) and soil coring techniques allows comments to be made on the advantages and disadvantages of the two techniques.

The profile wall counting technique advantages are: i) instant measurement, ii) easy to see rooting depth and width, iii) observations provide root distribution and existing root area or structure, iv) no need for expensive equipment, v) root profile obtained can be used as basic material for interpreting root data and the effect of soil type on root distribution. The disadvantages are: i) requires large holes/pits to be dug, ii) measurements are subjective and depend on operator skill in particular, as a selective decision is required when counting fine root branches that exist in the form of clusters,

iii) root counts do not provide sufficient data to estimate root surface area and iv) it was not effective if water table was temporarily high. Results are therefore not easily compared with other studies.

The soil coring technique is probably the most frequently used method of root sampling and produces measurements that are less dependent on subjective judgements of the operator. The soil cores can be divided into appropriate sections, and after washing, the fresh root length or density and dry root weight in different horizons can be estimated with simple equipment. The soil root corer developed by Matthew (1992) and used in the Hawke's Bay experiment had the following advantages i) no large pits or holes were required ii) provided quantitative root weight data iii) a single operator can do job in a day. Whereas, the disadvantages were i) a heavy driving hammer is required to penetrate in the dry soils ii) driving hammer weight is 20 kg and operator fatigue sets in limiting sample numbers that can be taken. In contrast, the Aslam's developed root corer (Aslam, 2003) used in the Manawatu experiment overcame the disadvantages of Matthew's corer by i) using easily cutting head when penetrated in the soil ii) single operator driven with less body fatigue because the driving hammer weight is only 9 kg.

Briefly, based on the field experience during field work, making root measurements by Aslam's root corer was easy, involved less fatigue than the alternatives, and provided quantitative data on root length and dry weight that could differentiate between maize and sweet corn root systems in the silt loam texture soil. Therefore, the Aslam's root corer is recommended for use in other root studies of cereal crops.

5.4.2 Cultivar differences in root biomass and rooting depths

5.4.2.1 Root biomass

In both the field experiments (Hawke's Bay and Manawatu), maize had significantly more roots than sweet corn, expressed as root count numbers or root dry weights in the Hawke's Bay (Table 5.1 and 5.2), and root dry weights and root length densities in the Manawatu (Table 5.3 and 5.4). At 50 DAS, the plant establishment stage (V3-V5 stage) in the Manawatu experiment, the maize root biomass was 3 times greater than that of sweet corn (Chapter 3, Table 3.13). In the same experiment, at sweet corn maturity stage (140 DAS); the sweet corn root biomass was 30% less than that of the maize respectively (Table 5.3).

5.4.2.2 Rooting depth

Marked differences in the rooting depth of two cultivars were also observed in the Manawatu field experiment (150 DAS). Maize and sweet corn roots penetrated to 1.5 and 1.0 m depth, respectively. Maize had thicker roots with overlapping between the plants, whereas, sweet corn had a similar but thin root structure with less roots overlapping between the plants. As early as 1926, Weaver reported that maize has widely spreading, deeply penetrating and much branching root system. A lateral spread of 1.3 m on all sides of the plant is possible, and a root penetration depth of 1.5 to 1.8 m is common (Weaver, 1926). According to Weaver (1926), sweet corn has a similar root system, but less widely spreading roots with a root depth equal to the height of the crop. Pellerin and Pages (1996) also reported maize roots had lateral spread of 0.6 m and maximum depth of 1.3 m at silking time during their field experiment in East of France. Therefore, the different rooting depths observed here for maize and sweet corn were not unusual and suggest that maize and sweet corn roots have the potential to penetrate easily to these depths at least in the Manawatu sandy loam.

During the 2002-03 growing season in the Manawatu region, the soil water contents in the root zone remained close to permanent wilting point (0.19 m^3/m^3), especially during later stage of growth (cob filling) period for maize (Chapter 3, Table 3.10). The dry conditions, or low soil moisture content, were mainly caused by below average rainfall

during January to April, 2003 (Chapter 3, Table 3.9). The dry soil conditions experienced during this period may have stimulated root elongation to those deeper depths for both cultivars in search of water (Weaver, 1926; Pellerin and Pages,1996). More details are on the trends in crop water use and depth of water extraction discussed in Chapter 6, section 6.4.4.

5.4.2.3 Penetration resistance

Penetration resistance is an important property used in studies of soil structure to predict differences in seedling and root growth (Gibbs, 1986; McLaren and Cameron, 1996). Some studies have reported relationships between penetration resistance and root growth, crop yields and soil physical properties descriptive of tilth (Karlen et al., 1994; Unger, 1996). There are no standard numerical penetration resistance values that identify compaction as root or yield limiting for maize or sweet corn. However, compaction in the root zone has been found to limit root growth as roots will only grow easily where the penetration resistance is less than 3 MPa (Leonard, 2001).

In the Manawatu experiment, the penetration resistance measurements suggest that root growth of either cultivar was not constrained by the soil physical conditions (Figure 5.5). Although, soil penetration resistance increased markedly with depth from 0.48 MPa (0-100 mm) to 2.06 MPa (500-600 mm) in that experiment, no readings were found that approached the 3 MPa limit at which root growth is constrained. Further, no differences in penetration resistance were observed between the replicates, indicating spatially uniform soil structure, and texture and bulk density across the plots of the experiment site.

5.4.3 Root system development

There were differences in the root system development between the two cultivars in the Manawatu and in the Hawke's Bay experiments.

In the Manawatu field experiment, between 110 and 140 DAS there was no significant change in maize root growth, but in the sweet corn, the root weight increased by 30% (Figure 5.8). The limited maize root development (8 kg root DM/kg) between 110 and

140 DAS was probably due to the drier soil conditions under maize during that season, as the soil water content remained lower with maize throughout the sampling period (Chapter 3, Table 3.10). This was because early in the growing season, the maize developed greater plant dry matter yield and greater root biomass, and therefore, more rapidly extracted water from soil early on (canopy closure for maize and sweet corn were at approximately 75 and 90 DAS, respectively). The increase in sweet corn root weight (413 kg root DM/ha) from 110-140 days was associated with i) a more moist soil condition under sweet corn than in the drier maize profile during that period, and ii) the plants earlier reproductive stage and the increased demand for nutrient and carbohydrate storage for further tiller development.

The sweet corn root systems growth between 110 to 140 DAS was consistent with greater P uptake by sweet corn than maize during this period (reported in Chapter 4, section 4.4.1), where sweet corn took up 8 kg P/ha between 110 to 140 DAS compared with 6 kg P/ha of total P uptake with maize. One possible explanation is that although the sweet corn root system was smaller, the sweet corn roots grew into new areas of non P depleted soil during 110-140 day period and therefore took up more P per unit root length during this period (see more discussion in Chapter 6). Alternatively the greater soil water content under sweet corn would have maintained a higher diffusion co-efficient for P through the soil to the roots. Generally, these results are consistent with other maize root growth and development studies. For example, research studies have reported that rapid development of maize roots occurs during the first 8 weeks after sowing (Anderson, 1987), and maximum size of the maize root system was reached between 11 and 13 weeks after planting and decreased after 14 weeks i.e. 98 DAS (Mengel and Barber, 1974).

Root: shoot ratio is used to indicate i) a favourable environment for root growth and nutrient uptake, ii) the efficiency of the root system for supporting shoot growth and yield (Anderson, 1988). This issue is further discussed in section 5.4.5.

In the Manawatu experiment, there were no significant differences in root: shoot weight ratios between the two cultivars during different growth stages (Figure 5.9). Maximum root: shoot ratio in both the cultivars occurred at 110 DAS indicating that root growth per unit increase of shoot growth was more in the vegetative period of development.

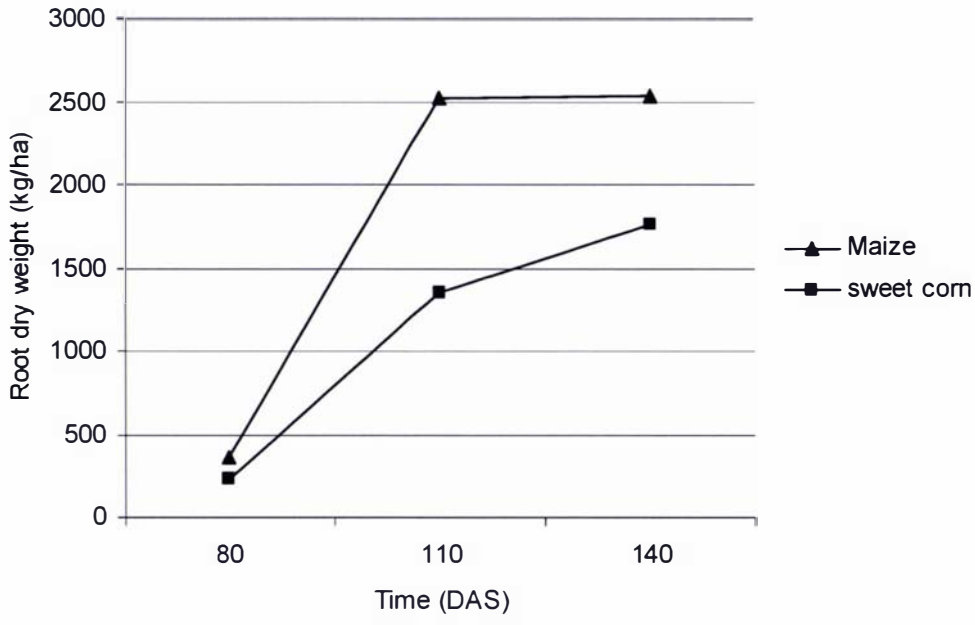


Figure 5.8 Maize and sweet corn total root dry weight (kg/ha) at 80, 110 and 140 DAS (0-400 mm depths) in the Manwatu experiment. Results are presented as the means of 3 P treatments.

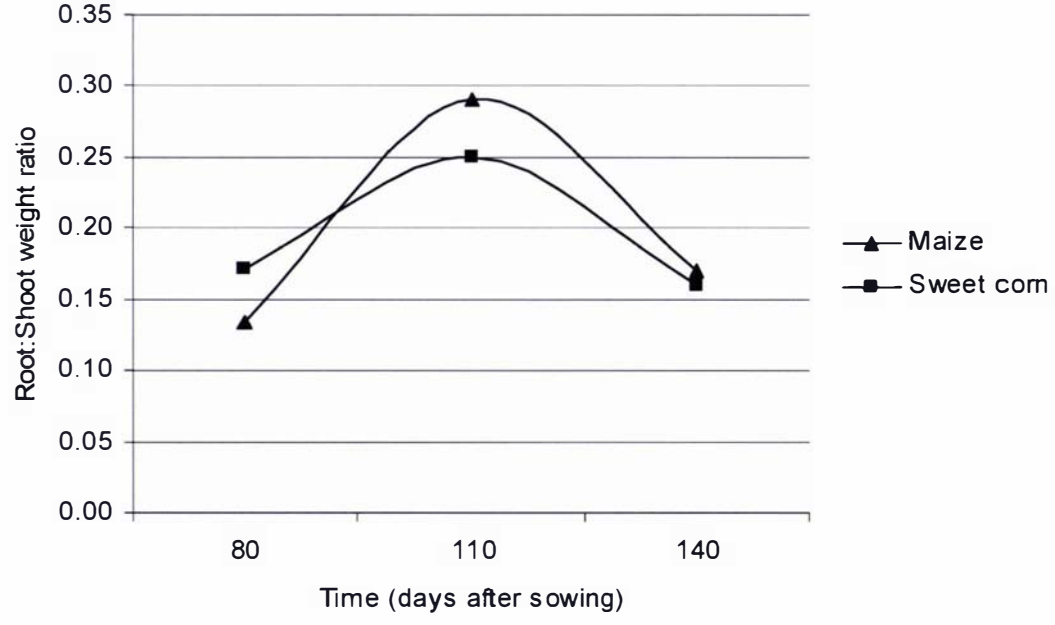


Figure 5.9 Root: shoot ratios at 80, 110 and 140 DAS in the Manawatu experiment. Results are presented as the means of 3 P treatments.

Perhaps, in the later stages senescence and repartitioning of nutrients from vegetative to reproductive parts lessened the nutrient requirement demand placed on the root system. In the Manawatu experiment, the root: shoot ratios ranged from 0.13 to 0.29 for both cultivars during different growth periods. Large variations existed in root: shoot weight ratios. These were associated with the large variation in the root dry weights obtained for both cultivars. Root: shoot ratios can vary depending on maize plant age and variety from 0.15 to 0.30 (Warneke and Barber, 1974). Maize root: shoot ratios decreased with time during growth from 0.44 to 0.15 in solution culture (Warneke and Barber, 1974).

It has already been discussed that maize had significantly higher above ground dry matter yields than sweet corn throughout all sampling periods in both field experiments (Chapter 3, section 3.4.1). In this section it has been observed that these above ground yields are also reflected in the larger root biomass of maize. The root weight results support the notion that the two cultivars differ in their genetic potential to produce both shoot and root biomass when climatic characteristics are similar. As explained earlier (Chapter 3), it is common for maize genotypes to differ in plant characteristics i.e. shoot and root biomasses. Several studies have reported differences in the shoot and root dry weights of different maize genotypes (Burris, 1977; Baria-Szabo et al., 1990). More recently, Costa et al. (2002) demonstrated that maize genotypes bearing the leafy trait had greater root lengths and surface areas than the conventional hybrid. Therefore, the results found in both field experiments support the conclusion that these two cultivars (maize and sweet corn) differ genetically in the morphological and physiological characteristics of their shoot and root systems.

5.4.4 Root system response to P fertiliser

In this study, there were no root growth responses to fertiliser P in the Hawke's Bay and Manawatu experiments (Table 5.1 and 5.3) (Plate 5.12), however, some responses under maize were observed in the Hawke's Bay experiment (Table 5.2). Overall, the maize and sweet corn root systems were not responsive to the addition of P fertiliser application in those conditions. Literature indicates that there are two P supply conditions to which maize root systems may respond. Increased root growth may be stimulated under low soil P status as the plant adapts to low P supply (Anghinoni and Barber, 1980; Mackay and Barber, 1985; Baligar, 1987; Rosolem et al., 1994). Alternatively, increased P supply to P deficient soils may stimulate both root and shoot growth (Hajabbasi and Schumacher, 1994; Colombo et al., 2000).

The lack of root growth responses to fertiliser P in both cultivars in Hawke's Bay and Manawatu experiments could be due to i) adequate soil P status for maize and sweet corn root growth and development, or ii) some other factors constraining the P responsiveness of root growth. These other factors were already discussed at length in relation to crop yield (Chapter 3, section 3.4.6) and are not covered here again. No evidence of yield constraining factors other than the dry soil conditions between 110-140 DAS in the Manawatu can be provided.

Evidence of maize root system responses to fertiliser P deficiency in field is very scarce. Most studies regarding maize root system (root length/biomass) response to P fertiliser have been laboratory based (Anghinoni and Barber, 1980; Mackay and Barber, 1985; Baligar, 1987; Fusseder et al., 1988; Zhang and Barber, 1992; Rosolem et al., 1994), and from those studies, some reported increases in root system size with P fertilisation, whereas, other reported negligible change (Chapter 2, Table 2.8).

There was no increase in the dry matter yields (shoot biomass) with P fertiliser application for either maize or sweet corn (Chapter 3) in the current experiments. Taken with the results in this Chapter, the results suggest that neither shoot nor root growth were responsive to P fertiliser under those soil field conditions. It is concluded that the existing soil P status for both field experiments were adequate for maize and sweet corn

shoot and root growth. The Olsen P tests values > 11 mg P are adequate for optimum root development and expression of maximum yield potential.

Plate 5.12 Maize and sweet corn root systems at V6-V7 stages showing the lack of responses to fertiliser P in the Manawatu fine sandy loam soil during season of 2002-03.

Using the information gained from the literature review and observations made in the Hawke's Bay and Manawatu field experiments, a conceptual model is proposed, which describes the influence soil P status may have on maize shoot and root growth (Figure 5.10).

Photosynthesis and translocation of carbohydrates to various plant parts are used for construction and maintenance of plant tissues. For maize and sweet corn, the crop biomass increases by about 1.6 t/ha for every 100 MJ of solar radiation (Reid et al., 2001a; b). Under optimum nutrient and photosynthesis conditions, there will be an abundance of metabolic carbohydrates leading to development of optimum plant structural growth (biomass), and ultimately provide maximum yield (Figure 5.10). Under optimum conditions when plant P demand is met by soil P supply (P sufficiency) the edaphic/hormonal control of carbohydrate allocation to shoot or root remains unaffected (see ideas of Grindlay, 1997). In contrast, P deficiency limits photosynthesis which limits carbohydrate supply for leaf and root growth. In addition, P deficiency also influences the edaphic/hormonal control of the allocation of carbohydrate such that the allocation to roots is increased. This allows higher root:shoot ratios to develop.

In the Manawatu experiment, there is a general trend indicating higher root:shoot ratios for the control treatment receiving no P fertiliser (maize and sweet corn root:shoot ratios, 0.22 & 0.19, respectively) than the 70 kg P/ha treatment (maize and sweet corn root:shoot ratios, 0.17 & 0.15, respectively). However the differences in root and shoot weights were not significantly influenced by fertiliser P addition. It is suggested that when grown under severe P deficiency conditions, the root: shoot ratios for maize could be as high as 0.30 as reported in the literature (Anderson, 1988). Fletcher et al. (2002) have reported that Olsen P levels of 6 mg P/L canopy development of sweet corn was constrained by P deficiency. Fletcher (2005) reported an increase of both kernel yield and crop biomass to increasing P supply. Unfortunately Fletcher et al. (2005) did not measure root biomass. Thus lack of marked differences in root:shoot ratios between fertiliser treatments is perhaps also an indication that the plant P nutrition was not markedly constrained in the P control treatments (initial Olsen P 10-15 mg P/kg soil i.e. zero P fertiliser application plots).

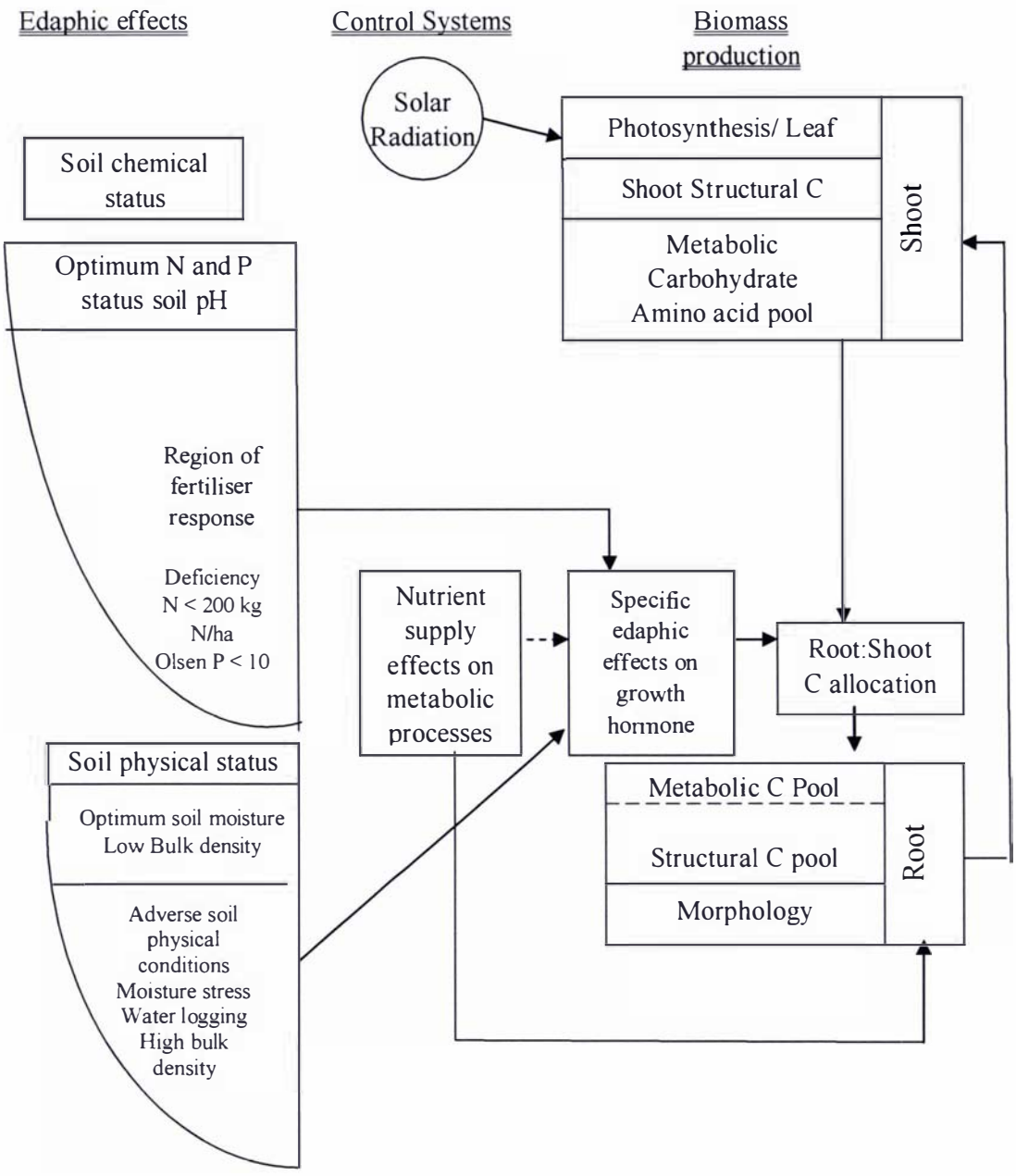


Figure 5.10 Conceptual diagram showing P deficiency effects on the maize plant and subsequent effects on root growth.

Control process ⟹ Nutrient supply -----→ Carbohydrates flow ⟶

5.4.5 Root system P uptake efficiency

In the Manawatu experiment, the P uptake efficiency (kg P/kg root) was calculated as the amount of P uptake per unit root dry weight at 0-400 mm soil depth (Gourley et al., 1994). This index reflects the efficiency of maize and sweet corn root systems in P uptake during different crop growth stages. There were no significant differences between maize and sweet corn in P uptake efficiency (Figure 5.11), indicating that the root system of each cultivar had a similar ability to absorb P from the soil. There were large variations in P uptake efficiency, which were due to large co-efficients of variation (37-50%) in the root dry weight replicates. P application rate had no effect on P uptake efficiency for both cultivars. P uptake efficiency decreased with time. This means that the roots were more P efficient at earlier stages compared to later. This is probably related to P depletion around existing root length. As the plant matures, the percentage of root length in P depleted soil increases (Tinker and Nye, 2000).

Results in this section suggest that P uptake efficiency is a good indicator to assess the ability of a plant root system to remove or acquire soil P, but as found in Chapter 4, under the conditions of two experiments the two cultivars had similar total P uptake and similar P uptake efficiencies. Similar P uptake efficiencies indicate that further studies to investigate differences in cultivar rhizosphere processes (Trolove et al., 2003) in this study would have been unwarranted.

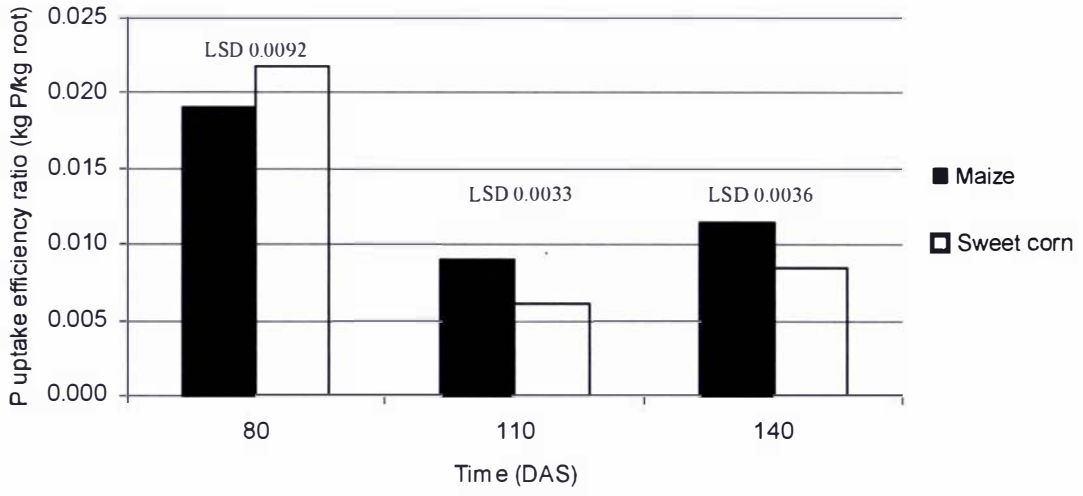


Figure 5.11 Root system P uptake efficiency ratios during crop growth in Manawatu. Results are presented as the means of 3 P treatments.

5.5.6 Conclusions

The hypothesis presented in beginning of this Chapter that maize and sweet corn differ in their root system is supported by both experiments. Maize had a bigger root system (root biomass) which developed earlier than that of sweet corn. Maize also had thicker roots which penetrated more deeply than sweet corn in the Manawatu fine sandy loam soil. The differences in the root system were genetic for both cultivars. Despite differences in root systems, both cultivars had similar P uptake efficiency and were similarly infected with mycorrhizal fungi. Overall, maize and sweet corn roots have similar potentials to extract soil P per unit root length. The lack of root system response to fertiliser P indicates that Olsen soil P test of 10-15 mg P/kg soil is adequate for maize and sweet corn root growth and development.

The Manawatu field experiment demonstrated that enhanced root growth may occur under moist soil conditions and an interaction between soil moisture content and soil depth may introduce variability in the development of the maize or sweet corn root system.

CHAPTER 6

INTERACTIONS BETWEEN CROP WATER USE AND NITROGEN AND PHOSPHORUS UPTAKE BY MAIZE AND SWEET CORN

6.1 Introduction

In New Zealand, water stress sometimes reduces the yield of maize and sweet corn (Jamieson et al., 1995; Reid et al., 2001a; b; Stone et al., 2001). A soil water balance model allows the timing of such stress periods to be simulated. To compute the soil water balance for a crop, one needs to know the amount of water stored in the soil at the time of planting and the daily evapotranspiration and water input (rainfall or irrigation) over the crop growing period. For maize and sweet corn, growth rates are often reduced when the root zone water storage drops below 50 and 60%, respectively, of the total available water holding capacity (Reid et al., 2001a; b). Reid et al. (2001a; b) suggest that water stress typically commences when there is a soil water deficit of 90 mm relative to field capacity for both corn and sweet corn. Furthermore, they found that the yield of maize and sweet corn dropped by between 350 and 500 kg/ha for every extra 10 mm of deficit greater this threshold.

Mathematical simulation of natural processes, or 'modelling', has been widely used in agricultural research for many years. It allows extrapolation of the experimental time frame, and provides possible answers to questions such as what happens when changes in the system occur (Jones, 1983). Soil water balance models are useful tools for irrigation scheduling and for predicting water deficits and their effects on plant growth. Thus soil water balance models are important farm management tools (Woodward et al., 2001). A variety of soil water balance models are described in the literature, ranging from simple to detailed models (e.g. Scotter et al., 1979; Akinremi and McGinn, 1996; De Jong and Boostsma, 1996; Allen et al., 1998; Moir et al., 2000a; Moir et al., 2000b; Scotter and Heng, 2003).

In Chapters 3 and 4, the results indicated that for both cultivars (maize and sweet corn) dry matter yield and P uptake were lower in the Manawatu experiment than in the

Hawke's Bay experiment. One reason for the lower yields in the Manawatu experiment may have been soil water content limitation, which occurred during the latter crop growth stages. In this Chapter, the simple FAO-56 soil water balance model (Allen et al., 1998), subsequently referred to as FAO-56, is used to predict when water uptake started to limit crop yield and from which soil horizon nutrients were taken up in the Manawatu experiment.

6.2 The central equations

Two key equations from FAO 56 are used here, one describing crop evaporation and the other the soil water balance.

The single crop coefficient approach in FAO 56 is used here, so crop evaporation (E_c) in mm/d is given by Equation (81) in FAO 56. Thus the first key equation is

$$E_c = K_s K_c E_o \qquad \text{(equation 6.1)}$$

Here K_s is the water stress coefficient taking into account the effect of water stress on evaporation; K_c is the crop coefficient taking into account any differences between the evaporation rate of non-stressed maize or sweet corn crops and the reference crop evaporation (due to for instance incomplete crop cover); and E_o is the reference crop evaporation in mm/d. The two coefficients are dimensionless.

The second key equation describes the soil water balance. It gives the root-zone soil water deficit at the end of day i (D_i) as

$$D_i = D_{i-1} + E_c + P - R \qquad \text{(equation 6.2)}$$

where D_{i-1} is the deficit on the preceding day (mm); P is the deep percolation (drainage) out of the root zone on day i (mm); and R is the rainfall on that day (mm). Note this equation is equation (85) in FAO 56, with the simplifying assumptions that surface runoff, capillary rise and irrigation were all negligible. The permeable nature and deep water table of the Manawatu fine sandy loam used, and the lack of irrigation, make these assumptions reasonable in this study.

Deep percolation of excess rainfall is assumed to bring the soil back to field capacity by the end of the day on which the rainfall occurs. Thus P equals zero unless $(R\text{-}E_c) > D_{i\text{-}1}$, otherwise $P = R - E_c - D_{i\text{-}1}$.

6.3 Evaluating the parameters in FAO-56

Suggested values for many of the parameters for corn and sweet corn are given in FAO-56. Those suggested values have mostly been used here. In a few cases a slightly different approach has been taken, as described below.

6.3.1 Reference crop evaporation (E_o)

The reference crop evaporation (evapotranspiration) was computed using the Priestley and Taylor (1972) equation, as described by Scotter et al. (2000) from daily meteorological data collected by AgResearch Grassland, Palmerston North. The Priestley-Taylor method was used because it requires fewer independent weather observations than the Penman Monteith equation favoured in FAO 56, but has been shown to be almost as accurate in Palmerston North (McNaughton et al., 1979).

6.3.2 Crop coefficient (K_c)

The crop coefficient (K_c) is defined as the ratio of the unstressed crop evapotranspiration to the reference crop evaporation (E_o), and represents an integration of the effects of characteristics such as crop height, albedo, canopy area and soil evaporation. Three anchor values for K_c are required to construct the crop coefficient curve. These are values during the initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$) and at the end of the late season stage ($K_{c\ end}$).

Table 12 in FAO-56 (1998) gives the approximate values of K_c to be used for estimating E_c during preliminary or planning studies. These values are for non-stressed crops cultivated under good agronomic and water management conditions and achieving maximum crop yield. For maize, the recommended values are $K_{c\ ini} = 0.9$, $K_{c\ mid} = 1.2$ and $K_{c\ end} = 0.60$. Similarly, for sweet corn, the values are $K_{c\ ini} = 0.9$, $K_{c\ mid} = 1.15$ and $K_{c\ end} = 1.05$. The primary sources from which these values in FAO-56 were obtained are Doorenbos and Pruitt, 1977; Wright, 1981; Pruitt, 1986 and Snyder et al., 1989.

6.3.3 Water stress coefficient (K_s)

The water stress coefficient takes account of the reduced evaporation when soil water becomes limiting. K_s =1 when there is readily available water present in the root zone, and $K_s < 1$ reflects a water stress period when all the readily available water has been exhausted. Once the total amount of available water has been used, $K_s = 0$. The estimation of K_s for day i used the daily water balance computation for the root zone. K_s was calculated using equation (84) in FAO 56 as

$$K_s = 1, \; D_i \leq W_R \qquad \text{(equation 6.3)}$$

$$K_s = (W_T - D_i)/(W_T - W_R), \; D_i > W_R \qquad \text{(equation 6.4)}$$

where W_T and W_R are the total and readily available water storage capacities of the root zone respectively, described further below; K_s is transpiration reduction factor dependent on available soil water (0-1); and D_i is root zone depletion (deficit) on day i (mm).

6.3.4 Total and readily available water storage capacities (W_T and W_R)

Total available water storage capacity (W_T) is the equivalent depth of water (mm) that a crop can extract from its root zone. If the soil is wetter than the field capacity, the excess water usually drains within a few days from the root zone. In simple terms, when the soil in the root zone is at permanent wilting point, the plant roots can extract no further soil water. Therefore, the total available water storage capacity in the root zone is usually defined as the difference between the equivalent depths of water in the root zone when the soil is at field capacity and permanent wilting point. W_T is thus estimated by equation (82) in FAO 56 as

$$W_T = (\theta_{FC} \cdot \theta_{PWP}) \, Z_R \qquad \text{(equation 6.5)}$$

where θ_{FC} is the soil water content at field capacity (m^3/m^3); θ_{PWP} is the soil water content at permanent wilting point (m^3/m^3); and Z_R is the effective rooting depth (mm).

Although roots can extract available water until permanent wilting point is reached when necessary, crop water uptake and plant growth are usually reduced well before all the available water is extracted. When the soil water content drops below a threshold value often referred to as the stress point (θ_{SP}), soil water can no longer be transported quickly enough towards the roots to respond to the transpiration demand from the leaves, and the crop begins to experience water stress. Thus the readily available soil water holding capacity can be defined as

$$W_T = (\theta_{FC} - \theta_{SP})\, Z_R \qquad \text{(equation 6.6)}$$

Allen et al. (1998) define the parameter p as W_R/W_T, and note that p normally varies from 0.3 for shallow rooted plants at high rates of crop evapotranspiration (> 8 mm/day) to 0.7 for deep-rooted plants at low rates of crop evapotranspiration (< 3 mm/day). They suggested p values of 0.55 for maize (with 1.0-1.7 m root depth), and 0.50 for sweet corn (with 0.8-1.2 m rooting depth). These values correspond closely to the value of 0.54 reported for maize crop in New Zealand (Reid et al., 2002).

To provide estimates of field capacity, stress point and permanent wilting point, soil samples (air dried, passed through 2 mm sieve) collected from the experimental site were brought to pressure potentials of -5, -100 and -1500 kPa respectively using pressure plate apparatus (Table 6.1) as explained by McLaren and Cameron (1996). Field measured bulk density values were used to change the gravimetric water contents into volumetric water contents. Note that the average value for stress point falls half way between field capacity and permanent wilting point, implying a value of 0.5 for p, the same value as that suggested for sweet corn in FAO 56, as mentioned above. Field soil water content (m^3/m^3) under dry conditions (on 11.3.03 when the model predicted soil water deficit under maize was 240 mm) and under wet conditions (on 17.12.03 when the predicted soil water deficit was less than 2 mm) at the experimental site were also measured to provide field estimates of field capacity, permanent wilting point and the total available water storage capacity as shown in Table 6.2.

Table 6.1 Laboratory determined soil volumetric water content (m^3/m^3) at different pressure potentials for soil samples from Manawatu fine sandy loam soil.

Soil depth (mm)	-5 kPa (field capacity)	-100 kPa (stress point)	-1500 kPa (wilting point)	[1]AWC (m^3/m^3)
0-100	0.39	0.29	0.19	0.20
100-200	0.37	0.30	0.20	0.17
200-300	0.31	0.23	0.17	0.14
300-400	0.31	0.22	0.12	0.19
Mean	0.35	0.26	0.17	0.18

[1]Available water content (AWC) is difference between field capacity and wilting point

Table 6.2 Field measured soil volumetric water content (m^3/m^3) for dry and wet soil conditions at the experimental site (Manawatu fine sandy loam soil).

Soil depths (mm)	Volumetric soil water content (m^3/m^3) [1]			
	Maize		Sweet corn	
	Dry condition (11.3.03)	Wet condition (17.12.03)	Dry condition (11.3.03)	Wet condition (17.12.03)
0-100	0.17	0.38	0.20	0.38
100-200	0.22	0.38	0.26	0.38
200-300	0.21	0.45	0.24	0.45
300-400	0.20	0.36	0.22	0.36
400-600	0.26	0.42	0.26	0.42
600-800	0.28	0.38	0.28	0.38
800-1000	0.29	0.46	0.29	0.46
1000-1200	0.33	0.43	-	-
Mean (depth weighted)	0.26	0.41	0.26	0.41
Total W (mm)	312	495	258	409
[2] PWP (mm)	204	204	170	170
Net Wa (mm)	108	291	88	239
[3] Field deficit	183		151	
[4] Model deficit	240		196	

[1]Mean of 2 replicates, [2]laboratory determined value, [3]on 11.3.03 and [4] FAO-56 model predicted values

Note that in Table 6.1, the difference between the water content at –5kPa (approximately field capacity) and –1500 kPa (approximately permanent wilting point) is fairly uniform in the top 400 mm of soil. Although measurements were not made using soil from below 400 mm depth, examination of the soil profile showed that the soil texture was quite uniform from 400 mm to 1200 mm depth. However, the field soil water content values for the 200-400 mm depths (of Table 6.1 and 6.2) measured at a predicted field soil water deficit of 0 (i.e. θ_{FC} at 17.12.03) were greater than the laboratory values determined at –5kPa tension.

FAO 56 suggests typical effective rooting depth values of about 1.2 m for maize and 1.0 m for sweet corn, respectively. To run the FAO-56 soil water balance model with realistic soil water content values, the field determined field capacity values (Table 6.2) and laboratory determined permanent wilting point values (Table 6.1) were used to calculate plant available water for rooting depths of 0-1200 mm for maize and 0-1000 mm for sweet corn (equation 6.5 and 6.6). The model estimated W_T values of 291 mm for maize and 239 for sweet corn, with the corresponding values for W_R 160 and 119 mm, respectively.

There is a factor that the above estimates do not take into account, however, the C horizon of Manawatu sandy loam is a coarse sand. This drains and becomes non-conductive at a pressure potential close to zero, which has the effect of increasing the field capacity of the fine sand in the B horizon above by about 55 mm (Clothier et al., 1977). At the site used for the experiment described, the boundary between the B and C horizons is at about 1.2 m depth. Thus it is likely that the above estimates of both the total and readily available water holding capacities could be lower than actual.

6.3.5 Topsoil water balance

As stated in the introduction, the reason for the water balance computations was to ascertain when root uptake was predominantly from the topsoil and when it was predominantly from the subsoil. So as well as calculating the daily soil water deficit for the whole rootzone, the deficit in the topsoil 0-150 mm depth was also estimated. This was again done by running the soil water balance equations given above, but assuming that $W_T = W_R = 28.5$ mm for 0-150 mm. Note that putting an effective rooting depth of

150 mm into equation 6.6 gives about this W_T value. Due to the root density being greatest in the top 150 mm of soil, maize and sweet corn tend to exhaust the available water from there before drawing on water deeper down in the profile.

6.3.6 Model implementation

The above-mentioned equations were formulated in an Excel spreadsheet to obtain daily estimates for E_c, D_i and K_s during the life of the maize and sweet corn crops.

The model was run with a starting date of 26.8.2002 when the soil water deficit was close to zero. The model, with its inputs and outputs is on the enclosed floppy as Appendix 6.1.

6.4 Results and discussion

6.4.1 Predicted and measured plant available water during the growing season

The simulated daily values for the equivalent depth of plant-available water stored in the whole root zone of 0-1200 mm, and in just the top 150 mm of soil, for the maize and sweet corn are shown in Figure 6.1 and 6.2. Before discussing the significance of these simulations, it is of relevance to see if these simulated values are consistent with the measured soil water content data presented earlier (Chapter 3, Table 3.10) and later (Table 6.2).

6.4.2 Root zone available water (simulated vs observed)

For the whole root zone (0-1200 mm), the only measurement taken during the growing season was on 11.3.03. Another measurement was made on 17/12/2003 after a number of heavy rainfalls had brought the soil back to the field capacity (Table 6.2). The net available water (W_a) under maize and sweet corn root zone was calculated by simply subtracting from the total water content and the permanent wilting point water content (Table 6.2).

Figure 6.1 and 6.2 shows the model predicted and measured available water (mm) in whole root profile for both cultivars. The measured net available water on 11.3.03 (135 DAS) was 108 mm for maize (0-1200 mm) and 88 mm for sweet corn (0-1000 mm) (Figure 6.1 and 6.2). The model simulated values for maize (48 mm) at 0-1200 mm and sweet corn (44 mm) at 0-1000 mm were approximately half the measured values on that particular date (11.3.03). The probable reasons for this discrepancy are firstly, the crop water use coefficients (K_c) may have overestimated plant water use. Secondly, the coefficient for soil limited water use, K_s, for maize and sweet corn may require a different method of calculation than the relationship used in equation 6.1 relating K_s to the fractional remaining W_a (θ_{FC}.θ_{PWP}). Thirdly the measurements of soil water content made on 11.3.03 show that approximately 55% of W_R in the maize profile was recharged in the 800-1200 mm soil depth and the corresponding figure for sweet corn (800-1000 mm depth) was 44 %. Thus it appears that the model overestimated the ability of both crops to extract water from the lower soil depths for maize (800-1200 mm) and sweet corn (800-1000 mm), respectively.

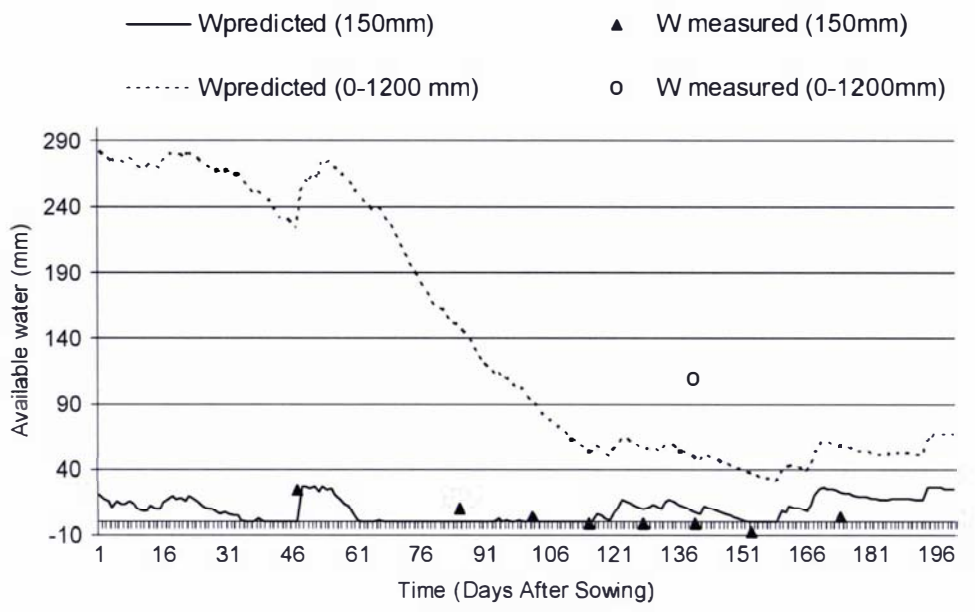


Figure 6.1 FAO-56 soil water balance predicted and measured available water at 0-150 and 0-1200 mm soil depths under maize during season 2002-03 (Manawatu experiment).

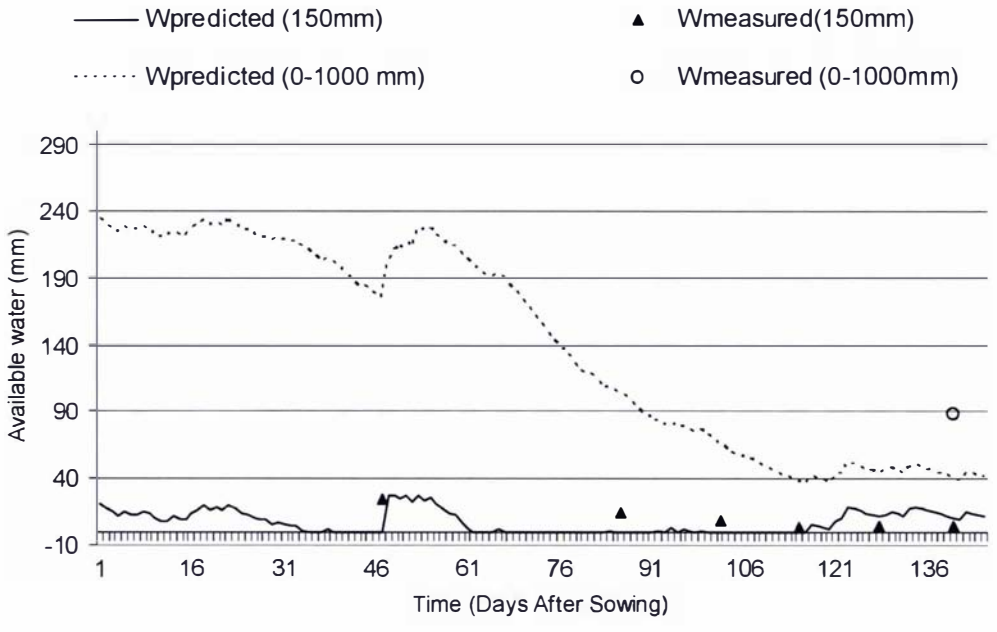


Figure 6.2 FAO-56 soil water balance predicted and measured available water at 0-150 and 0-1000 mm soil depths under sweet corn during season 2002-03 (Manawatu experiment).

6.4.3 Topsoil available water (simulated vs observed)

At 46 DAS, the measured soil water contents in the 0-150 mm soil depth indicated that there was 24.5 mm of available water under both cultivars. This measured value is consistent with the FAO-56 model simulated value at that particular time under both cultivars as shown in Figure 6.1 and 6.2. The next measurement dates (from 80 to 175 DAS), both the measured and simulated values suggest negligible water availability in the top 150 mm for both the maize and sweet corn. The negative measured values (-1 to –8 mm for the maize crop for the next three measurements between 115-153 DAS suggests that evaporation from the soil surface had dried the topsoil out below permanent wilting point. This is something not taken into account by the model for topsoil water content. Not taking into account the extra water needed to replace this evaporation probably partly explains the last measured maize soil value being lower than the simulated value at 170 DAS.

In summary, where there are discrepancies between the measured and simulated available soil water values, there appear to be reasonable explanations for them. Provided these discrepancies are kept in mind, the FAO 56 simulation can be used to indicate when it is likely that plant water (and so nutrient) uptake would have been mostly from the topsoil, and when a dry topsoil would have forced the roots to extract water from lower down in the soil profile.

6.4.4 Trend in crop water use and depth of water extraction

The crop water use was estimated by accumulating simulated crop evapotranspiration (E_c) values from 1 to 140 DAS. The model simulation suggested that the crop water use from 1 to 140 DAS by maize and sweet corn were 449 and 407 mm, respectively. The model predicted that maize used 42 mm more water than sweet corn. There was a similar trend observed in soil water content measured on 140 DAS (11.3.03) at 0-400 mm depths (Table 6.2). The observed difference in field soil water content values at 0-400 mm depth (140 DAS) was only 12 mm.

In the topsoil (0-150 mm), the simulated maximum root zone depletion (D_i) is 28.5 mm (Manawatu fine sandy loam soil), which is the difference between the laboratory determined θ_{FC} (0.38) and θ_{PWP} (0.19). Note that the field and laboratory θ_{FC} and θ_{PWP}

values are similar for 0-150 mm soil depth (Table 6.1 and 6.2). A similar value (27 mm) was also found by Sumanasena (2003) for the same soil type. Therefore, it is assumed that when D_i reached 27 mm, all available topsoil soil water (0-150 mm) would have been used by the crop. The FAO-56 soil water model predicted that during the peak crop growth period, the topsoil (0-150 mm) was at or below θ_{PWP} from 61 to 115 DAS (22.12.02 to 14.2.03) (Figure 6.1 and 6.2). From this stage onward, the majority of water used by the plants has to be derived from lower soil depths. The model simulated W_a values are in reasonable agreement with the measured W_a values for the 0-150 mm depth determined from soil volumetric water content measured for the growth interval 80-110 days (Figure 6.1 & 6.2).

6.4.5 Trend in plant and root growth

Despite the 0-150 mm simulated and measured soil water content being below or close to θ_{PWP} during the period 80-110 days, the maize shoot and root mass (0-400 mm) increased by 5880 kg/ha and 2217 kg/ha, respectively (Table 6.3). Similarly, the sweet corn shoot and root mass (0-400 mm) also increased by 4280 kg/ha and 953 kg/ha, respectively (Table 6.4). The major increase in root mass in both varieties, in terms of growth in root dry matter and as percentage contribution to total increased root mass, occurred in the topsoil 0-100 mm depth. Smaller increases were recorded in the lower depths (Table 6.3 and 6.4). This suggests that sufficient soil water was available for root growth in the top soil despite the dry soil conditions for both cultivars.

Table 6.3 Plant and root dry matter yield at 80 and 110 days after sowing in maize control treatment (Manawatu).

Soil depths (mm)	Root dry matter (kg/ha)			Plant dry matter (kg/ha)	
	80 DAS	110 DAS	Inc ease as % of total change	80 DAS	110 DAS
0-100	286	1824	69.4		
100-200	81	525	20.0	2720	8600
200-300	49	231	8.2		
300-400	21	74	2.4		
Total	436	2653	100	-	-

Table 6.4 Plant and root dry matter yield (kg/ha) at 80 and 110 days after sowing in sweet corn control treatment (Manawatu).

Soil depths (mm)	Root dry matter (kg/ha)			Plant dry matter (kg/ha)	
	80 DAS	110 DAS	Increase as % of total change	80 DAS	110 DAS
0-100	188	793	63.5		
100-200	28	221	20.3	1220	5500
200-300	15	114	10.4		
300-400	6	62	5.8		
Total	237	1190	100	-	-

6.4.6 Trend in nutrient N and P uptake during growing season

It was noted that the simulated and measured W_a (mm) values in the 0-150 mm soil depth were at or below θ_{PWP} for much of the period between 80-110 DAS and remained at or close to θ_{PWP} for the period 110-140 DAS, respectively. Due to dry soil conditions at 0-150 mm, it is likely that very little N mineralisation occurred at this soil depth. Despite soil dryness at 0-150 mm, there was a little nitrate-N depletion between 80 to 140 DAS for maize (8 kg N/ha) and sweet corn (11 kg N/ha) (Figure 6.3 and 6.4). In contrast, significant soil nitrate-N depletion for maize (57 kg N/ha) and sweet corn (80 kg N/ha) occurred in the 150-300 mm soil depth (Figure 6.3 and 6.4), and 22 (maize) with 4 kg N/ha (sweet corn) in the 300-400 mm soil depths (Figure 6.3 and 6.4), which remained above θ_{PWP} from 80 to 140 days. There was a reasonable similarity between the sum of NO_3-N depleted in the 0-400 mm soil depths and plant N uptake (between 80-140 DAS) (Figure 6.7). The average (all treatments) soil NO_3-N depletion for maize and sweet corn were 87 and 95 kg N/ha between 80 to 140 DAS, respectively. For the same period, the plant N uptake in maize (99 kg N/ha) and sweet corn (120 kg N/ha) was greater than nitrate-N depletion (Figure 6.7), presumably because nitrate-N was also taken up from below 400 mm soil depths or some mineralised N was taken up over this period. Alternatively some of the nitrate uptake may have been replaced by mineralisation in moist soil horizons (lower soil depths). The soil nitrate-N was not

measured at 80 DAS below 400 mm soil depths and the soil nitrate-N status ranged from 11- 48 kg N/ha (0.48 to 5.04 ppm as NO_3-N) for the 400 -1200 mm at 140 DAS.

Between 80 and 140 DAS, there was significant depletion of the Olsen extractable P pool at all three soil depths (Figure 6.5 and 6.6). Unlike soil nitrate-N, there was significant P depletion in the dry topsoil as well as P depletion in the lower soil depths. However, Olsen P depletion was slightly greater at lower soil depths (150-300 & 300-400 mm) compared to the upper soil depth (0-150 mm) (Figure 6.5 and 6.6). In maize, from 80-140 DAS, 17% of the observed decrease in Olsen P in the whole soil profile (0-400 mm) came from the dry topsoil (0-150 mm) (Figure 6.9). For NO_3-N, only 9% of the depletion came from this soil depth (Figure 6.8). It is reported/known that 90 to 98% of P movement to roots in soil is by diffusion and only 1% by mass flow (Barber, 1980).

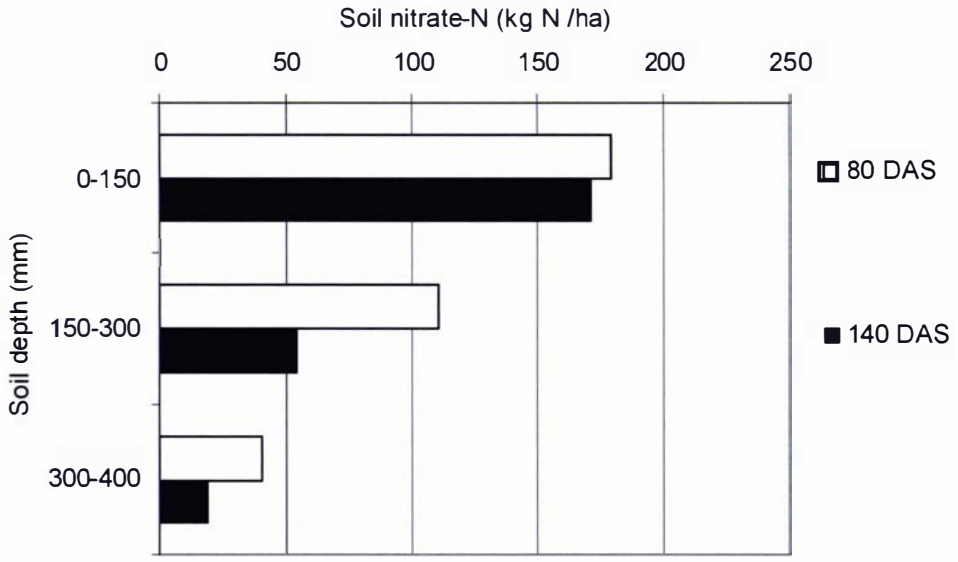


Figure 6.3 Amount of KCL-extractable soil nitrate-N in 0-150, 150-300 and 300-400 mm soil depths at 80 and 140 DAS under maize during 2002-03 season.

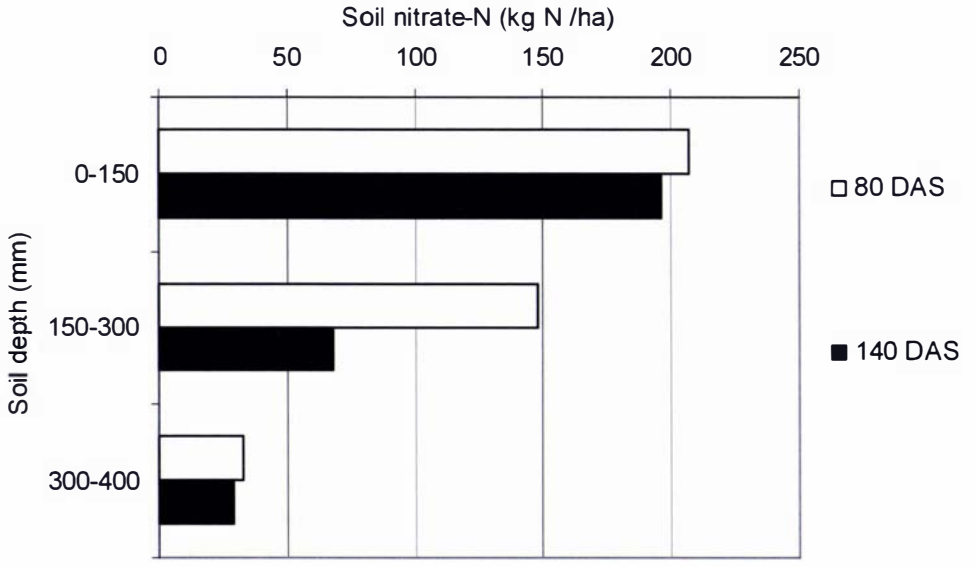


Figure 6.4 Amount of KCL-extractable soil nitrate-N in 0-150, 150-300 and 300-400 mm soil depths at 80 and 140 DAS under sweet corn during 2002-03 season.

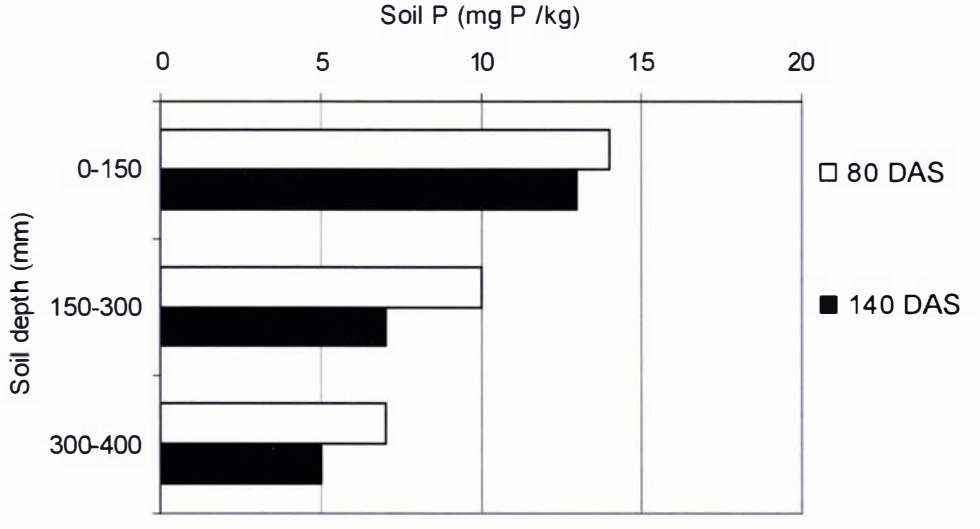


Figure 6.5 Amount of $NaHCO_3$ extractable phosphate in 0-150, 150-300 and 300-400 mm soil depths at 80 and 140 DAS under maize during 2002-03 season.

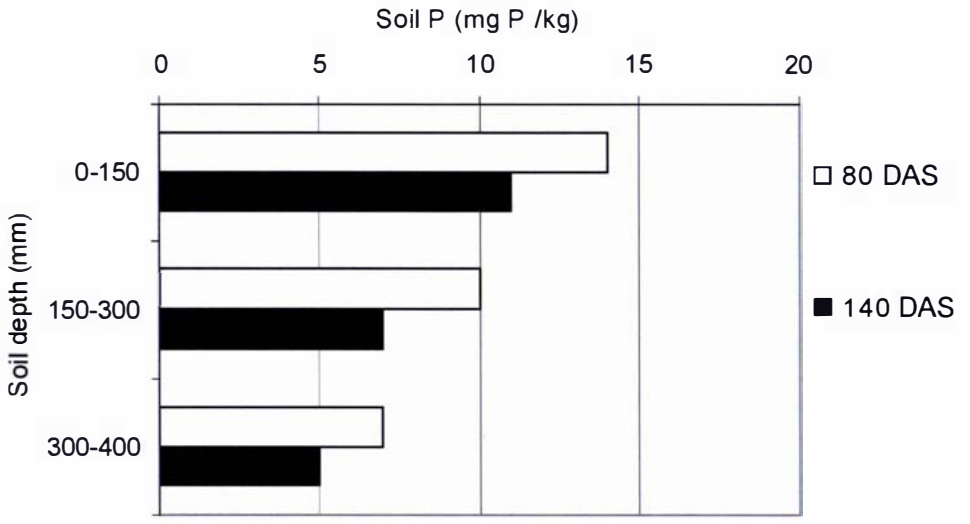


Figure 6.6 Amount of $NaHCO_3$ extractable phosphate in 0-150, 150-300 and 300-400 mm soil depths at 80 and 140 DAS under sweet corn during 2002-03 season

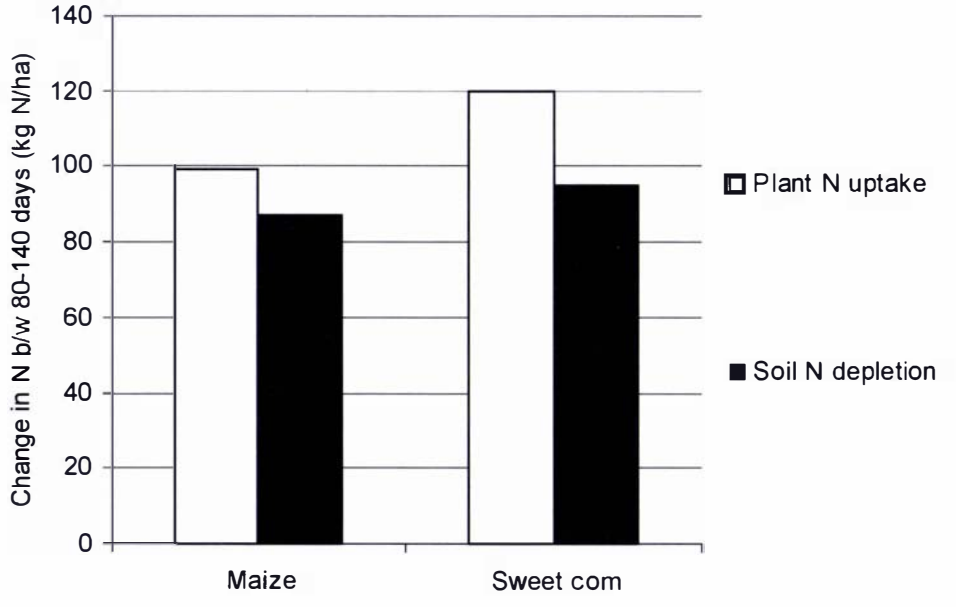


Figure 6.7 The changes in extractable soil nitrate-N (0-400 mm) and N uptake by maize and sweet corn between 80 and 140 DAS during 2002-03 season.

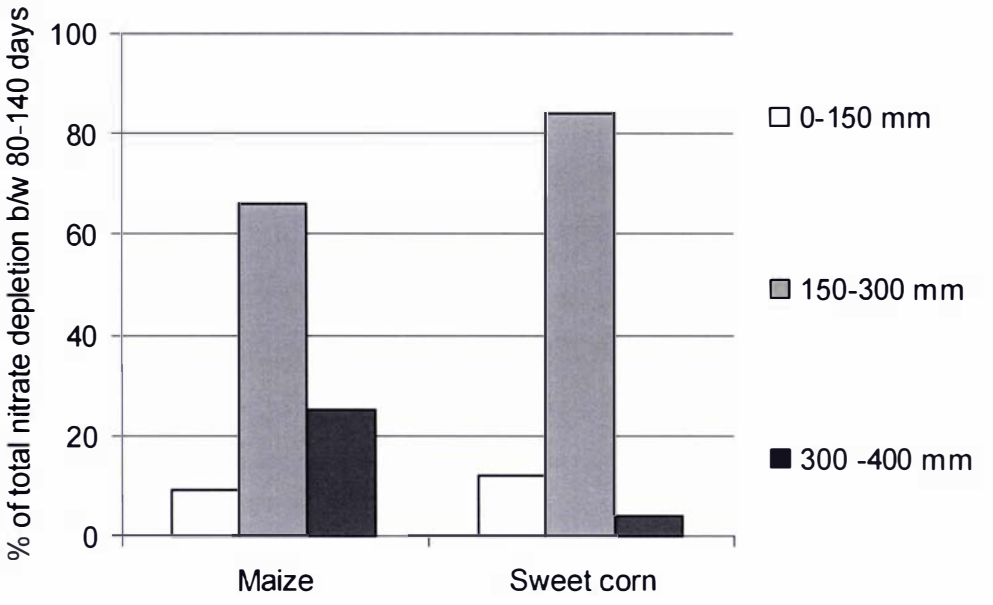


Figure 6.8 Contribution of soil depths (0-150, 150-300 and 300-400) to total soil nitrate-N depletion by maize and sweet corn between 80 and 140 DAS during 2002-03 season in the Manawatu.

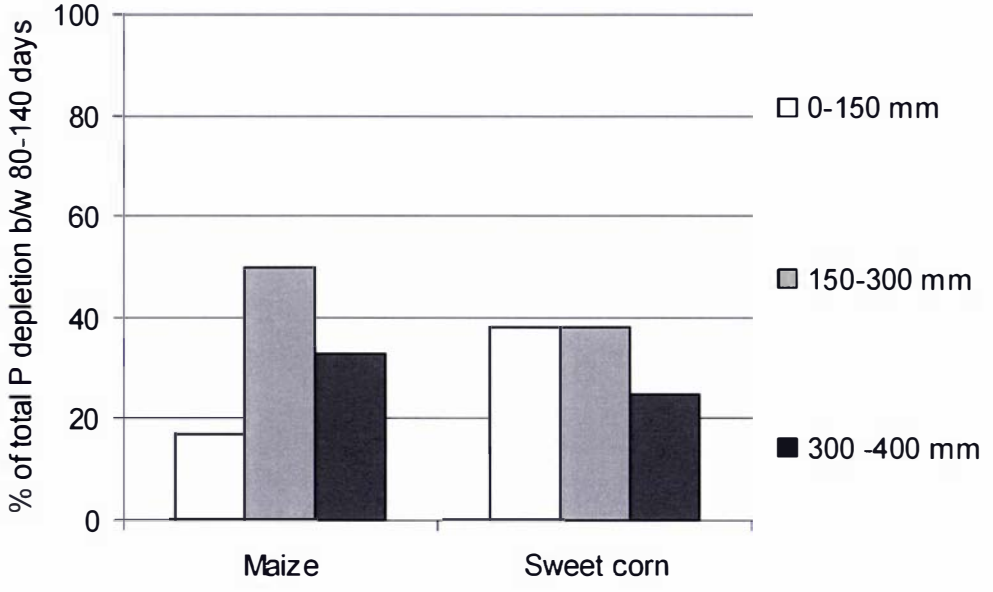


Figure 6.9 Contribution of soil depths (0-150, 150-300 and 300-400) to total Olsen P depletion by maize and sweet corn between 80 and 140 DAS during the 2002-03 season in the Manawatu.

In contrast N moves in the soil primarily by mass flow (Barber, 1984) of nitrate; nitrate and ammonium are readily soluble and ammonium is rapidly nitrified to nitrate (Clark, 1990). The literature also shows that P moves only limited distances from its source during a growing season i.e. estimated to be 5 mm or less (Barber, 1976). Therefore, the zones close to the roots are important for P diffusion and uptake. The contrasting soil NO_3-N and soil P depletion at 0-150 mm soil depth under the two cultivars reflects the two different mechanisms i.e. mass flow for soil nitrate and diffusion for soil P. Nye and Tinker (1977) showed that the rate of P uptake from a narrow cylinder around a root is controlled by the soil water content and steepness of the P concentration gradient. In contrast, NO_3-N uptake was much more dependent on water uptake and the concentration of NO_3-N in the water. Concentration gradients for NO_3-N away from the roots are not steep and would drive little diffusion.

P diffusion rates to the root in the centre of a cylinder of soil will limit P uptake rates. As soil P is depleted, the rate will decline and P uptake rates can only be maintained by new roots exploring soil where P has not previously been depleted. Thus for P uptake, the root length and rates of new root length development will be extremely important in maintaining overall P supply. The results in the Manawatu experiment show that the root length density (RLD) (cm/cm^3) was significantly higher (75%) under maize compared with sweet corn at 80 DAS (for detail see Chapter 5, Table 5.4). This is consistent with the P uptake by maize at 80 DAS being twice that of sweet corn (6 v 3 kg P/ha) (Chapter 4, Table 4.4). Between 80 to 110 days, the P uptake for both cultivars was approximately equal (7 kg P/ha) and between 110 to 140 days, the sweet corn took up more P (3 kg P/ha) than maize. This is also consistent with the root weight data, as sweet corn grew greater new root biomass (413 kg root DM/ha) than maize (8 kg root DM/ha) between 110 and 140 DAS (Chapter 5, Table 5.3). Between 80 and 140 days, there was a greater amount of Olsen extractable P depleted under sweet corn compared with maize at 0-150 mm soil depth (Figure 6.9), also of the total amount of Olsen P depleted 38% came from the 0-150 mm depth with sweet corn and only 17% with maize. However, there was no consistent relationship between P uptake and RLD or ΔRLD. Thus other factors (such as soil water content, or soil P content) must have exerted a strong influence over rates of P uptake in sweet corn between/over the 110 to 140 DAS period.

At 80, 110 and 140 DAS, the surface (0-100 mm depth) soil water content under sweet corn remained higher compared with maize (Chapter 3, Table 3.10). This higher volumetric soil water content (θ) would have allowed greater P diffusion to sweet corn roots. The rate of diffusion is strongly influenced by the diffusion coefficient (cm^2/sec) as explained by Fick's first and second laws of diffusion (Barber, 1984). The effective diffusion coefficient (D_e) for phosphate in soil can be described thus:

$$D_e = D_l f_l \theta / b \qquad \text{(equation 6.7)}$$

where D_l (cm^2/sec) is the diffusion coefficient of phosphorus in water (0.89×10^{-5} cm^2/sec); θ is volumetric soil water content (m^3/m^3); f_l is impedance factor due to tortuosity of diffusion path through soil aggregates and calculated by; $f_l = 1.6\,\theta - 0.172$ for light texture soils as shown by Barber (1984); and b is the soil surface phosphate buffer power (average of $\Delta P_S/\Delta P_L$ where P_S is the concentration of exchangeable phosphate per unit weight of soil and P_L is the concentration of phosphate in the soil solution) which can be found using desorption P isotherms (Bolan et al., 1999). Below is a consideration of how the terms f_l, θ and b may have differed between varieties and times in the Manawatu experiment.

At 80 DAS, the surface soil (0-100 mm) moisture contents under sweet corn and maize were 0.26 and 0.24 m^3/m^3, while at 140 DAS the soil water contents under sweet corn and maize decreased to 0.20 and 0.17 m^3/m^3, respectively (Chapter 3, Table 3.10). This means that topsoil surface conditions remained drier under maize than sweet corn. The topsoil solution P concentration for the Manawatu soil with an Olsen P of 11 mg P/kg soil is assumed to be approximately P_L = 0.01mmole/L (Sumanasena, 2003). The Freundlich equation relationship (derived by Bolan et al., 1999) can describe P sorption in the Manawatu silt loam soil as

$$P_S = K P_L^{\,n} \qquad \text{(equation 6.8)}$$

Therefore, phosphate buffer power (b) can be expressed as

$$b = d\,\Delta P_S / d\,\Delta P_L = K n P_L^{\,n-1} \qquad \text{(equation 6.9)}$$

where K = 13.2 and n = 0.52 for the Manawatu sandy loam soil (Bolan et al., 1999). This indicates a phosphate buffer power value of 63, which is comparable with the reported value (60) for a typic Udipsamment (sandy loam soil) given by Barber (1984).

Using these values in the equation 6.7, D_e is calculated for the maize and sweet corn topsoil (Table 6.5). These D_e values are comparable with the D_e values for phosphate reported to range from 1 x 10^{-8} to 1 x 10^{-10} cm^2/sec (Barber, 1984). Because of the high buffer power of phosphorus in soil, D_e for phosphorus is usually much smaller than D_e for nutrients such as nitrate and potassium. It is clear from Table 6.5 that as the season progressed and the soil dried out, the slower rate of drying under the sweet corn meant that D_e stayed greater than that under maize. Other researchers have demonstrated that lower soil water reduces P diffusion through the soil to the root surface (Olsen et al., 1965; Hira and Singh, 1977; Barber, 1980). Reduced P fertiliser responses under low soil water have been reported by Simpson and Pinkerton, 1989 and Dodd et al., 1992. Supporting evidence of the effect of soil water on P uptake also comes from Olsen et al. (1961), who found that the total P uptake by corn seedling roots declined (50%) as soil water potential decreased from -33 kPa to -300 kPa. Similarly, Mackay and Barber (1985) also reported that the total plant weight and total P uptake by corn increased as soil water content was raised from 0.22 m^3/m^3 to 0.27 m^3/m^3.

One important question still remains. How did maize take up P from the 0-150 mm depth when the water content was below θ_{PWP} ? Recent research by Bernd et al. (2002) indicates that oats and sugar beet had continued to take up P under dry soil conditions. They propose that water and root mucilage are exuded by plant roots under dry soil conditions. In dry soil condition, these mucilages absorb sufficient amounts of water, which facilitates P transport and P uptake (Bernd et al., 2002). A few other studies have also noted P uptake from dry soil in laboratory experiments. For example, Mackay and Barber (1985) demonstrated P uptake by maize from soil at water content of 0.22 m^3/m^3, when corn growth was limited by a shortage of water. Similarly, Thorup (1969) also reported P uptake by tomato roots grown in soil at 4, 12 and 22 % soil water content, where 4 and 12% were growth limiting soil water conditions.

Table 6.5 Effect of soil water content on effective diffusion coefficient (D_e) influencing the rate of P uptake by maize and sweet corn roots.

Time (DAS)	Cultivars	Soil water content (m^3/m^3)	D_e (cm^2/sec)
80 DAS	Maize	0.24	0.71×10^{-10}
//	Sweet corn	0.26	0.90×10^{-10}
140 DAS	Maize	0.17	0.24×10^{-10}
//	Sweet corn	0.20	0.41×10^{-10}

6.5 Conclusions

The FAO-56 soil water balance model simulated crop water use well and produced simulated soil water content similar to the measured values for the topsoil surface depth. Rates of water extraction simulated by crop water use coefficients may overestimate somewhat the rates of plant water extraction from the lower soil depths. The model, however, allowed interpolation between measured soil water values and assisted in estimating the dates when water stress occurred at different soil depths.

By comparing the simulated and measured soil water contents and root biomass over time, it was evident that both maize and sweet corn were able to grow new roots in soils that were at wilting point or close to wilting point. This new root growth was probably responsible for a significant amount of P taken up by the plants in their latter stages of growth. To take up P from the dry topsoil, the maize and sweet corn roots may have translocated water from moister soil layers and exuded water and mucilage in the drysoil to facilitate P diffusion to the root surface. In contrast, because the soil's nitrate uptake is more dependent on water uptake, little or no soil nitrate was taken up by the roots growing in dry soil zones. In the latter growth stages, as the soils dried out, small differences in volumetric water content in topsoils between cultivars probably resulted in significant differences in P uptake. Thus cultivars that establish slowly, using less soil water for early growth, may be capable of taking up more late season P in a dry year for cob filling than those that reached canopy closure earlier in the season.

CHAPTER 7

SUMMARY AND SUGGESTIONS FOR FUTURE ACTIVITY

7.1 Summary

The overall objective of this study was to assess the growth and yield responses of maize and sweet corn to soil P status as influenced by fertiliser P application. Maize and sweet corn are two cultivars of the same species (*Zea mays* L.) but currently have contrasting P fertiliser recommendations in New Zealand. For growing sweet corn, the recommended target Olsen P test values are 26-35 mg P/kg soil, whereas, for maize, the values are 10-15 mg P/kg soil.

Three key hypotheses were developed in this study; i) maize and sweet corn differ in the responsiveness to P fertiliser (maize requires less P than sweet corn to grow i.e. maize is more internally P efficient), ii) this differences arises because maize and sweet corn differ in plant P uptake and external P use efficiency and iii) these differences in turn arise because the cultivars differ in root system structure (root biomass and distribution) (Chapter 2, section 2.9). The first hypothesis was tested in two different field experiments.

The first field experiment conducted in the Hawke's Bay in 2001-02 examined crop growth and yield responses to fertiliser P applications. The soil type was Te Awa silt loam and maize and sweet corn were planted at 87719 and 71124 plants/ha. The fertiliser P application rates were 100 and 200 kg P/ha and pre-plant soil P status (Olsen P test) was 13 mg P/kg soil. In this experiment, all other essential key variables for crop growth (soil water, fertiliser N and K application, climate) remained adequate throughout the growth period. The highest fertiliser P applications significantly raised the Olsen P test levels from 13 to a maximum of 45 mg P/kg soil.

Results from this first field experiment showed significant differences between cultivars in shoot and root biomass (dry matter yields) throughout growth. Maize had higher shoot and root dry matter yields than sweet corn. Overall, both cultivars grew and

yielded well; sweet corn fresh cob yield was 27 t/ha and maize grain yield of 16 t/ha was achieved. Differences in the total P uptake between the cultivars only occurred during establishment and vegetative stages and by 100 DAS similar amounts of total plant P were taken up (32-35 kg P/ha). Although, fertiliser P application increased the P uptake by both cultivars, it did not significantly increase yields (total crop dry matter, sweet corn fresh cob or maize grain yields). This suggested that a soil Olsen P status of 13 mg P/kg soil was adequate for growing maize and sweet corn under the conditions of this experiment.

The second experiment was conducted in the Manawatu region (season 2002-03) under pre-plant soil P status of 11 mg P/kg soil. The soil was a Manawatu sandy loam. In this experiment both maize and sweet corn were planted at the same density of 71124 plants/ha. Three main P fertiliser treatments (0, 15 and 70 kg P/ha) were applied to assess the fertiliser P responses on plant above ground (dry matter, sweet corn fresh cob and maize grain yields) and below ground (root biomass) characteristics. The fertiliser P addition of 15 and 70 kg P/ha increased the Olsen P test values from 11 to a maximum of 16 mg P/kg soil. Furthermore, seven P fertiliser treatments (0, 7.5, 15, 22.5, 30, 50 and 70 mg P/kg soil) were applied to produce a P limited growth response curve for both cultivars. All other essential nutrients for crop growth were sufficient in the soil and did not limit crop growth. However, low temperatures at plant establishment (October 2002) and water shortage during later growth stages (January to March) limited the dry matter yield and P uptake in that experiment.

Overall, results from this experiment also confirmed observations made in the earlier Hawke's Bay experiment that maize had higher shoot and root biomass than sweet corn. The sweet corn fresh cob yield of 28 t/ha and maize grain yield of 10 t/ha achieved were close to the marketable potential yields for these two cultivars for that region at 71124 plants/ha. Application of P fertiliser at 15 and 70 kg P/ha did not significantly increase the yields or P uptake by the crops. As in the Hawke's Bay experiment, the differences in P uptake between the cultivars occurred during establishment and vegetative growth stages with no significant differences in the total plant P uptake at 140 DAS (18-19 kg P/ha). This means that under these conditions (which included an inadequate soil water supply) a soil P status of 11 mg P/kg soil seemed to be adequate for both cultivars growth.

Based on the dry matter and fresh cob yields and crop P uptake in both experiments, it was concluded that a commercially acceptable sweet corn crop can be grown using the same phosphorus nutrition recommendations as maize. Thus these results do not support hypothesis that maize and sweet corn differ in their responsiveness to P fertiliser.

The marked differences in P uptake by both cultivars between location and season were considered to result from the slower accumulation of GDD in the Manawatu region, which forced both cultivars to continue growth during the low rainfall period of January to March, 2003. Soil water content values (average for both cultivars at 0-100 mm soil depth) measured at 80 DAS (0.25 m^3/m^3), 110 DAS (0.19 m^3/m^3) and 140 DAS (0.19 m^3/m^3) indicated that both cultivars had grown under water stress which may have been responsible for the lower yields and P uptake compared with those in the Hawke's Bay. To interpolate between the measured soil water content values and to establish the period of soil water stress, the FAO-56 soil water balance model was used to predict the water deficit periods during crop growth. The FAO-56 model closely estimated the soil water deficit period for the Manawatu experiment site under maize and sweet corn. The "model-predicted" and measured soil water deficits in the topsoil (0-150 mm) agreed reasonably well. The model was able to identify that the dates when the crops suffered water stress were from 267-697 GDD. The differences in measured and predicted soil water content between the two cultivars also indicated that early season (200-455 GDD) maize crop water use was higher than sweet corn because late season (455-930 GDD) soil water content remained higher under sweet corn. Despite late season topsoil dryness, Olsen P measurements to depth indicated P depletion in the dry topsoil as well in the lower soil depths. Of the total amount of Olsen P depleted, approximately 38% came from topsoil depth (0-150 mm) with sweet corn compared with 17 % with maize. This was attributed to the higher soil water content under sweet corn, which would have allowed greater P diffusion to sweet corn roots.

Observations made in both the Hawke's and Manawatu field experiments are very similar, showing that maize and sweet corn differ genetically in their dry matter yield and root characteristics. This results in faster establishment of maize and greater uptake of P early in crop growth. However, the P uptake by both cultivars at the sweet corn maturity stage (910 GDD in the Hawke's Bay and 930 GDD in the Manawatu) was similar. So over the whole growing season the root systems were equally effective at

absorbing P from soil. However, the maize was able to grow more dry matter per unit P taken up (greater internal P efficiency). In both experiments, the P fertiliser was not a yield limiting factor for plant and root growth for both cultivars. Therefore, it seems that, soil P status of 10 to 15 mg P/kg soil is adequate for growing maize or sweet corn in New Zealand arable cropping system. These findings are consistent with New Zealand recommendations (research studies) for growing maize; however, they differ with the recommendations for growing sweet corn. Therefore, some suggestions for future research are recommended.

7.2 Suggestions for future activity

The results from the Hawke's Bay and Manawatu experiments indicate that sweet corn growers could be advised to reduce fertiliser P inputs into sweet corn cropping system. These recommended reductions in P fertiliser use should not compromise commercial yields. It is suggested that the major sweet corn processors should initiate a phosphorus nutrient management program for sweet corn growers in their respective regions. The research data generated in this study could be added to the decision support software that provides fertiliser recommendations for sweet corn. For example, the Crop & Food Research (CRI) sweet corn calculator software, which currently does not take into consideration soil P fertility status.

Further field experiments on the effects of soil P status on sweet corn production at a number of other locations with different climatic regimes and soil types would be helpful to support the findings of this thesis. In particular, future studies might like to incorporate a wider range of soils and cropping histories in the Hawke's Bay and Gisborne regions - the main sweet corn growing areas. Further, the main focus should be to assess the response of fresh cob yield to fertiliser P in low P status soils. Separate rainfed and irrigation experiments may be required because seasonal soil water deficits will influence sweet corn yield and availability of P uptake. Incorporation of soil water balance models into crop decision support software will assist decisions on irrigation scheduling to maintain topsoil water contents that can improve external and internal P efficiency.

Fertiliser P application programs/plans for sweet corn production on a sustainable basis should be consistent with the Regional Council strategies to minimise P transport from cropping systems to drainage and surface runoff waters for long-term environmental sustainability and profitability.

During the study, the methodological challenge was to quantify accurately the maize and sweet corn root systems and root growth response to P fertiliser in the field. Two root corers (for soft and hard soil conditions) were developed, tested and used to measure the maize and sweet corn root systems in the Manawatu sandy loam soil conditions. Measurement of the root systems with "Aslam's soil corer" was effective for measuring maize and sweet corn root systems and their response to P fertiliser levels. The root corer worked well for taking soil and root samples from all depths. Further, this corer (Aslam's soil corer) allowed determination of the maximum rooting depth of two cultivars in Manawatu sandy loam soil, and the soil water content during the growth period. Additional measurements should be made of sweet corn and maize rooting depths with Aslam's soil corer throughout the growing season in the range of different soil types in which they are grown. This data will prove invaluable input for improving models of crop water use and the amounts of plant available water present in different soil depths.

REFERENCES

Abbott, L.K. and Robson, A.D. 1982. The role of vesicular-arbuscular mycorrhizal fungi in agriculture and the selection of fungi for inculation. *Australian Journal of Agricultural Research* 33:389-408.

Akinremi, O.O. and McGinn, S.M. 1996. Usage of soil moisture models in agronomic research. *Canadian Journal of Soil Science* 76:285-295.

Aldrich, S.R. and Leng, E.R. 1969. *Modern Corn Production.* Fourth printing. F & W Publishing Corporation, Cincinnati, Ohio, USA.

Allen, G.R., Pereira, S.L., Raes, D. and Smith, M. 1998. *Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56.* FAO, Rome. p87-134.

Alves, V.M.C., Parentoni, S.N., Vasconcellos, C.A., Filho, A.F.C.B., Pitta, G.V.E. and Schaffert, R.E. 2001. Mechanisms of phosphorus efficiency in maize. In: *Plant Nutrition-Food Security and Sustainability of Agro-ecosystems.* (Eds. W.J. Horst, M.K. Schenk, A. Burkert., N. Classen, H. Flessa, W.B. Frommer, H. Goldbach, H.W. Olfs, V. Romheld, B. Sattlemacher, U. Schmidhalter, S. Schubert , N.V. Wiren and L. Wittenmayer) Kluwer Academic Publisher, Netherland. p566-567.

Anderson, E.L. 1987. Corn root growth and distribution as influenced by tillage and nitrogen fertilization. *Agronomy Journal* 79:544-549.

Anderson, E.L. 1988. Tillage and N fertilization effects on maize root growth and root:shoot ratio. *Plant and Soil* 108:245-251.

Anderson, E.L., Kamprath, E.J. and Moll, R.H. 1985. Prolificacy and N fertilizer effects on yield and N utilization in maize. *Crop Science* 25:598-602.

Anonymous. 1979. *Soil and Plant Analysis at Ruakura.* New Zealand Ministry of Agriculture and Fisheries Bulletin.

Anonymous. 2000. *Agricultural Production Survey-Horticultural Statistics.* Statistics New Zealand.

Anuradha, M. and Narayanan, A. 1991. Promotion of root elongation by phosphorus deficiency. *Plant and Soil* 136:273-275.

Arnon, I. 1975. *Mineral Nutrition of Maize.* International Potash Institute, Bern/Switzerland.

Aslam, T. 2003. A simple and rapid technique to study maize and sweet corn root systems. *New Zealand Soil News* 51:159-160.

Atkinson, D. 1983. The growth, activity and distribution of the fruit tree root system. *Plant and Soil* 71:23-26.

Atkinson, D. 1991. Methodology for study of roots in field experiments and the interpretation of results. In: *Plant Root Growth. An Ecological Perspective*. (Ed. D. Atkinson). Blackwell Scientific Publications. London. p10-22.

Anghinoni, I. and Barber, S.A. 1980. Phosphorus influx and growth characteristics of corn roots as influenced by P supply. *Agronomy Journal* 72:685-688.

Baligar, V.C. 1986. Interrelationships between growth and nutrient uptake in alfalfa and corn. *Journal of Plant Nutrition* 9:1391-1404.

Baligar, V.C. 1987. Phosphorus uptake parameters of alfalfa and corn as influenced by P and pH. *Journal of Plant Nutrtion* 10:33-46.

Baligar, V.C., Duncan, R.R. and Fageria, N.K. 1990. Soil plant interaction on nutrient use efficiency in plants. In: *Crops as Enhancers of Nutrient Use*. (Eds. V.C Baligar and R.R Duncan). Academic Press. San Deigo, USA. p351-373.

Bansal, R.K. and Eagles, H.A. 1985. History and present status of maize production in New Zealand. In: *Maize Management to Market*. (Eds. H.A. Eagles and G.S. Wartt). Agronomy Society of New Zealand, Christchurch, New Zealand. Special Publication 4:3-6.

Barber, S.A. 1962. A diffusion and mass-flow concept of soil nutrient availability. *Soil Science* 93:39-49.

Barber, S.A. 1976. Efficient fertiliser use. In: *Agronomic Research for Food*. (Ed. F.L. Patterson). Special Publication. No 26. ASA, CSSA, SSSA, Madison, Wisconsin, USA. p13-29.

Barber, S.A. 1980. Soil plant interactions in the phosphorus nutrition of plants. In: *The Role of Phosphorus in Agriculture*. (Eds. F.E. Khasawneh, E.C. Sample, and E.J. Kamprath). ASA, CSSA and SSSA, Madison, Wisconsin, USA. p591-615.

Barber, S.A. 1984. Nutrient absorption by plant roots. In: *Soil Nutrient Bioavailability. A Mechanistic Approach*. (Ed. S.A. Barber). John Wiley & Sons, Inc., New York, USA. Interscience Publication. p55-210.

Barber, S.A. 1995. Phosphorus. In: *Soil Nutrient Bioavailibility–A Mechanistic Approach*. (Ed S.A. Barber). John Wiley & Sons, Inc., New York, USA. p400-414.

Barber, S.A. and Cushman, J.H. 1981. Nitrogen uptake model for agronomic crops. In: *Modeling Wastewater Renovation-Land Treatment* (Ed. I.K. Iskandar).Wiley-Interscience, New York, USA. p382-409.

Barber, S.A. and Silberbush, M. 1984. Plant root morphology and nutrient uptake. In: *Roots, Nutrient and Water influx and Plant Growth*. (Eds. S.A. Barber, and D.R. Bouldin). ASA, CSSA and SSSA, Madison, Wisconsin, USA. p205-300.

Baria-Szabo, G., Dolinka, J. B. and Odiema, M. 1990. Diallel analysis of seed vigour in maize. *Seed Science and Technology* 18:721-729.

Barry, D.A.J. and Miller, M.H. 1989. Phosphorus nutritional requirement of maize seedlings for maximum yield. *Agronomy Journal* 81:95-99.

Bar-Yosef, B., Sagiv, B. and Markovitch, T. 1989. Sweet corn response to surface and subsurface trickle phosphorus fertilization. *Agronomy Journal* 81:443-447.

Benson, G.O. and Pearce, R.B. 1987. Corn perspective and culture. In: *Corn: Chemistry and Technology* (Eds. S.A. Watson and P.E Ramstad). Amercian Association of Cereal Chemists, Inc., St Paul, Minnesota, USA. p1-31.

Berger, J. 1962. *Maize Production and Manuring of Maize*. Centre D' Etude de L' Azote 5, Geneva, Switzerland.

Bernd, S., Horst, L. and Norbert, C. 2002. Root regulate ion transport in the rhizosphere to counteract reduced mobility in dry soil. In: *Proceedings of the 17th WCSS Symposium Number 64*. Thailand:1245-1255.

Berta, G., Fusconi, A. and Hooker, J.E. 2002. Arbuscular mycorrhizal modifications to plant root systems: scale, mechanisms and consequences. In: *Mycorrhizal Technology in Agriculture: from genes to bioproducts*. (Eds. S. Gianinazzi, H, Schuepp, J.M. Barea and K. Haselwandter). Birkhauser Verlag, Basel, Switzerland. p71-85.

Bishop, R.F., Smeltzer, G.G. and Maceachern, C.R. 1972. Response of corn to nitrogen, phosphorus and potassium. *Canadian Journal Soil Science* 52:27-42.

Blair, G. 1993. Nutrient efficiency- What do we really mean? In: *Genetic Aspects of Plant Mineral Nutrition*. (Eds. P. J. Randall, E. Delhaize, R. A. Richards and R. Munns). Kluwer Academic Publishers, Dordrecht, Netherlands. p204-213.

Bohm, W. 1976. *In situ* estimation of root length at natural profiles. *Journal of Agriculture Science* 87:365-368.

Bohm, W. 1979. Profile wall methods. In: *Methods of Studying Root Systems. Ecological Studies 33*. (Eds. W Bohm). Springer-Verlag, Berlin, Germany. p48-60.

Bolan, N.S. 1991. A critical review on the role of mycorrhizal fungi in the uptake of phosphorus by plants. *Plant and Soil* 134:189-207.

Bolan, N.S., Naidu, R., Khan, M.A.R., Tillman, R.W. and Syers, J.K. 1999. The effects of anion sorption on sorption and leaching of cadmium. *Australian Journal of Soil Research* 37:445-460.

Bole, J.B. and Freyman, S. 1975. Response of irrigated field and sweet corn to nitrogen and phosphorus fertilisers in Southern Alberta. *Canadian Journal of Soil Science* 55:137-143.

Bray, R.H. and Kurtz, L.T. 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Science* 64:101-109.

Brooking, I.R. and McPherson, H.G. 1986. Sweet corn as a processing crop in the Manawatu. *Proceedings of the Agronomy Society of New Zealand* 16:1-5.

Brooking, I.R. and McPherson, H.G. 1989. The impact of weather on scheduling of sweet corn for processing 1. Quantifying the link between the rate of growth and environment. *New Zealand Journal of Crop and Horticultural Science* 17:19-26

Bruetsch, T.F. and Estes, G.O. 1976. Genotype variation in nutrient uptake efficiency in corn. *Agronomy Journal* 68:521-523.

Buman, R.A., Schumacher, T.E. and Riedell, W.E. 1994. A modified soil monolith technique for characterizing root systems. *Crop Science* 34:296-299.

Burris, J.S. 1977. Effect of location of production and maternal percentage on seedling vigour in maize hybrid. *Seed Science and Technology* 5:703-708.

Bundy, L.G., Tunney, H. and Halvorson, A.D. 2005. Agronomic aspects of phosphorus management. In: *Phosphorus: Agriculture and the Environment.* (Eds. J.T. Sims and A.N. Sharpley). ASA, CSSA and SSSA, Madison, Wisconsin, USA. p685-728.

Caradus, J.R. 1991. The inadequacy of using tissue phosphorus concentration as an indicator of efficiency of phosphorus use. In: Proceedings of the workshop *Soil and Plant Testing for Nutrient Deficiencies and Toxicities.* (Eds. R.E. White and L.D. Currie) Occasional report No 5, FLRC, Massey University, Palmerston North, New Zealand. p33-41.

Caradus, J.R. 1994. Selection for improved adaptation of white clover to low phosphorus and acid soil. *Euphytica* 77:243-250.

Chappell, P.L. 1985. Uses and processing of grain maize in New Zealand. In: *Maize Management to Market* (Eds. H.A. Eagles and G.S. Wartt). Agronomy Society of New Zealand. Christchurch, New Zealand. Special Publication 4:9-17.

Clark, R.B. 1983. Plant genotype differences in the uptake, translocation, accumulation and use of mineral elements required for plant growth. *Plant and Soil* 72:175-196.

Clark, R.B. 1990. Physiology of cereals for mineral nutrient uptake, use and efficiency. In: *Crops as Enhancers of Nutrient Use* (Eds. V.C. Baligar and R.R. Duncan). Academic Press. San Diego, California, USA. p131-209.

Clark, R.B. and Zeto, S.K. 2000. Acquisition of nutrients by arbuscular mycorrhizal plants. *Journal of Plant Nutrition* 23:867-902.

Clark, C.J., Smith, G.S., Prasad, M. and Cornforth, I.S. 1986. *Fertiliser Recommendations for Horticultural Crops.* Ministry of Agriculture and Fisheries. Wellington. p57-67.

Clothier, B.E., Scotter, D.R. and Kerr, J.P. 1977. Water retention in soil underlain by a coarse-textured layer: Theory and a field application. *Soil Science.* 123(6):392-398.

Colombo, B., Kiniry, J.R. and Debaeke, P. 2000. Effect of soil phosphorus on leaf development and senescence dynamics of field grown maize. *Agronomy Journal* 92:428-435.

Cornforth, I. 1998. *Practical Soil Management.* Lincoln University Press with Whitireia Publishing and Daphne Brasell Associates Ltd, New Zealand.

Cornforth, I.S. and Sinclair, A.G. 1984. *Fertiliser Recommendations for Pastures and Crops in New Zealand.* Ministry of Agriculture, Wellington, New Zealand. p6-15.

Cornforth, I.S. and Steele, K.W. 1981. Interpretation of maize leaf analyses in New Zealand. *New Zealand Journal of Experimental Agriculture* 9:91-96.

Costa, C., Dwyer, M. L., Zhou, X., Dutilleul, P., Hamel, C., Reid, M. L. and Smith, L, D. 2002. Root Development. *Agronomy Journal* 94:97-101.

Cumberland, G.L.B. and Douglas, J.A. 1970. *New Zealand Soil News* 18 (4):155-160.

Dawson-Mackie, L.A. and Atkinson, D. 1991. Methodology for study of roots in field experiments and the interpretation of results. In: *Plant Root Growth. An Ecological Perspective.* Special publication 10. (Eds. D. Atkinson). Blackwell Scientific Publications. London. p10-22.

De Jong, R., Bootsma, A. 1996: Review of recent developments in soil water simulation models. *Canadian Journal of Soil Science* 76:263-273.

Dechassa, N., Schenk, M.K., Claassen, N. and Steingrobe, B. 2003. Phosphorus efficiency of cabbage (*Brassica oleraceae* L. var. capitata), carrot (*Daucus carota* L.) and potato (*Solanum tuberosum* L.). *Plant and Soil* 250:215-224.

Denmead, O.T. and Shaw, R.H. 1960. The effect of soil moisture stress at different stages of growth on the development and yield in corn. *Agronomy Journal* 52:272-274.

Densley, D. 2002. Sustainability of continual cropping of maize for silage in the Waikato. In: Proceedings of the workshop *Dairy Farm Soil Management.* (Eds. L.D. Currie and P. Loganathan). Occasional Report No.15. FLRC, Massey University, Palmerston North, New Zealand. p111-126.

Dodd, M.B., Orr, S.J. and Jackson, B.L.J. 1992. Soil aluminimum, phosphate and moisture interactions affecting the growth of four white clover (Trifolium repens L.) lines. *New Zealand Journal of Agricultural Research* 35:411-421.

Doorenbos, J. and Pruitt, W.O. 1977. *Crop Water Requirements. FAO Irrigation and Drainage Paper No 24.* FAO, Rome, Italy.

Douglas, J. A., Dyson, C.B. and Sinclair, D.P. 1982. Effect of plant population on the grain yield of maize under high yielding conditions in New Zealand. *New Zealand Journal of Agricultural Research* 25:147-149.

Downes, M.T. 1978. An improved hydrazine reduction method for the automated determination of low nitrate levels in freshwater. *Water Research* 12:673-675.

Drew, M.C. 1975. Comparison of the effects of a localised supply of phosphate, nitrate, ammonium and potassium. *New Phytologist* 75:479-490.

Duncan, W.G. 1975. Maize. In: *Crop Physiology: Some Case Histories* (Ed. L.T. Evans). Cambridge University Press, Cambridge, UK. p23-50.

During, C. 1972. *Fertilisers and Soils in New Zealand Farming*. Government Printer, Wellington, New Zealand. p42-46.

Dyson, C.B. and Douglas, J.A. 1975. Comparison of systematic spacing and randomized block designs in a maize population study. *Proceedings of the Agronomy Society of New Zealand* 5:45-48.

Eagles, H. A. 1987. Population responses of maize hybrids in Manawatu. *Proceedings of the Agronomy Society of New Zealand* 17:1-6.

Eagles, H.A. and Hardacre, A.K. 1979a. Genetic variation in maize for early seedling growth at low temperature environment. *New Zealand Journal of Agricultural Research* 22:553-559.

Eagles, H.A. and Hardacre, A.K. 1979b. Genetic variation in maize for early germination and emergence at 10^0C. *Euphytica* 28:287-295.

Edmeades, G.O., 1972. *Maize in Manawatu. A field study of the effects of spacing and variety upon the growth of Zea mays* L., M. Agri. Sci. Thesis, Massey University, Palmerston North, New Zealand.

Ellis, J.R., Larsen, R.H. and Boosalis, M. 1985. Drought resistance of wheat plants inoculated with vesicular-arbuscular mycorrhizae. *Plant and Soil* 86:369-378.

Ferguson, J.E., Dickenson, D.B. and Rhodes, A.M. 1978. Genetics of sugary enhancer (su) an independent modifier of sweet corn (su). *Journal of Heredity* 69:377-380.

Fertiliser Recommendations for Horticultural Crops. 1986. Vegetables. (Eds. C.J. Clark, G.S. Smith, M. Prasad and I.S. Cornforth). Ministry of Agriculture and Fisheries, Wellington, New Zealand. p57-67.

Fletcher, A.L. and Moot, D.J. 2003. Sowing date and fertiliser effects on sweet corn phenological development. *Agronomy New Zealand* 32:35-41.

Fletcher, A.L, Moot, D.J. and Stone, P.J. 2002. Canopy development of sweet corn in response to phosphorus. *Agronomy New Zealand* 32:7-15.

Fletcher, A. 2005. *Understanding Challenger sweet corn yield, quality and phenology response to phosphorus.* PhD Thesis, Lincoln University, Christchurch, New Zealand.

Fohse, D., Claassen, N. and Junk, A. 1988. Phosphorus efficiency of plants. *Plant and Soil* 110:101-109.

Food and Agriculture Organisation of the United Nations (FAO). 1992. *Maize in Human Nutrtion.* FAO Food and Nutrition Series No 25. Rome, Italy. p6-9.

Fox, R L., Nishmoto, R.K., Thompson, J. R. and de la Pena, R. S. 1974. *Comparative External P Requirements of Plants Growing in Tropical Soils.* Transactions 10th International Congress on Soil Science 4. Moscow. p232-239.

Frossard, E., Brossard, M., Hedley, M.J. and Metherell, A. 1995. Reactions controlling the cycling of P in soils. In: *Phosphorus in the Global Environment.* (Ed. H. Tiessen). John Wiley & Sons Ltd. England. p107-138.

Fusseder, A., Kraus, M. and Beck, E. 1988. Reassessment of root competition for P of field-grown maize in pure and mixed cropping. *Plant and Soil.* 106:299-301.

Gavito, M.E. and Millar, M.H. 1998. Early phosphorus nutrition, mycorrhizae development, dry matter partitioning and yield of maize. *Plant and Soil* 199:177-186.

Gerdemann, J.W. 1968. Vesicular-arbuscular mucorrhiza and plant growth. *Annual Review. Phytopathology* 6:397-418.

Gianinazzi, S., Schuepp, H., Barea, J.M. and Haselwandter, K. 2002. *Mycorrhizal Technology in Agriculture: From Genes to Bioproducts.* Birkhauser Verlag, Basel, Switzerland.

Gibbs, R.J. 1986. *Changes in soil structure under different cropping systems.* PhD Thesis. University of Canterbury, Christchurch, New Zealand.

Gibbs, R.J. and Reid, J.B. 1992. Comparison between net and gross root production by winter wheat and by perennial ryegrass. *New Zealand Journal of Crop and Horticultural Science* 20:483-487.

Gourley, C.J.P., Allan, D.L. and Russelle, M.P. 1994. Plant nutrient efficiency: A comparison of definitions and suggested improvement. *Plant and Soil* 158:29-37.

Glover, J. 1959. The apparent behaviour of maize and stomata during and after drought. *Journal of Agricultural Science* 53:412-416.

Greenwood, E.A.N. 1976. Nitrogen stress in plants. *Advances in Agronomy* 28:1-35.

Griffiths, E. 2001. *Soils of the Heretaunga plains-a guide to their management.* Grifftech & Hawke's Bay Regional Council, Napier, New Zealand. p60.

Grindlay, D.J.C. 1997. Towards an explanation of crop nitrogen demand based on the optimization of leaf nitrogen per unit leaf area. *Journal of Agricultural Science, Cambridge* 128:377-396.

Hajabbasi, M.A. and Schumacher, T.E. 1994. Phosphorus effects on root growth and development in two maize genotypes. *Plant Physiology* 89:225-230.

Hanly, J.A. 2001. *Effects of green manure crops on short-term nitrogen availability in organic sweet corn systems.* M. Appl. Sc. Thesis. Massey University, Palmerston North, New Zealand.

Hansen, L.N. 2000. *Source-sink relationship in sweet corn (Zea mays L) for processing: plant density and nitrogen nutrition effect.* PhD, Thesis. Massey University, Palmerston North, New Zealand.

Hanway, J.J. 1962. Corn growth and composition in relation to soil fertility. II. Uptake of N, P and K and their distribution in different plant parts during the growing season. *Agronomy Journal* 54:217-229.

Hanway, J.J. and Olsen, R.A. 1980. Phosphorus nutrition of corn, sorghum, soybeans and small grains. In: *The Role of Phosphorus in Agriculture*. (Eds. F.E. Khasawneh, E.C. Sample and E.J. Kamprath). ASA, CSSA and SSSA, Madison, Wisconsin, USA p681-691.

Hanlon, E.A., Hochmuth, G.J., Obreza, T.A. and Chaplin, M.H. 2005. Phosphorus nutrition of vegetable crops and fruits. In: *Phosphorus: Agriculture and the Environment.* (Eds. J.T. Sims and A.N. Sharpley). ASA, CSSA and SSSA, Madison, Wisconsin, USA. p521-540.

Hardacre, A.K. and Eagles, H.A. 1989. The temperature response of young hybrid maize plant adapted to different climates. *New Zealand Journal of Crop and Horticultural Science* 17:9-17.

Hardacre, A.K., Sinclair, K.I. and van Tilbury, M.P. 1991. *Maize. A Guidelines for Growers.* Agricultural Bulletin No 8, DSIR Crop Research, Christchurch, New Zealand.

Harper, J.L., Jones, M., Hamilton, N.R.S. 1991. The evolution of roots and the problems of analysing their behaviour. In: *Plant Root Growth. An Ecological Perspective.* (Ed. D. Atkinson) Blackwell Scientific Publications, London. p10-22.

Hedley, M. J. 1998. Communication:19.153: *Study Guide Chemistry.* Massey University, Palmerston North, New Zealand:111-120.

Hedley, M.J., Hill, R. and Hill, G. 2002. Soil tests and environmental codes of practice. In: Proceedings of the workshop *Dairy Farm Soil Management.* (Eds. L.D. Currie and P. Loganathan). Occasional Report 15. FLRC, Massey University, Palmerston North, New Zealand. p363-371.

Hedley, M.J., Kirk, G.J.D. and Santos, M.B. 1994. Phosphorus efficiency and forms of soil phosphorus utilized by upland rice cultivars. *Plant and Soil* 158:53-62.

Hedley, M.J., Mortvedt, J.J., Bolan, N.S. and Syers, J.K. 1995. Phosphorus fertility management in agroecosystems. In: *Phosphorus in the Global Environment.* (Ed. H. Tiessen). John Wiley & Sons Ltd. England. p59-92.

Hepp, C. 2003. *Legume abundance in New Zealand summer-moist and summer-dry hill country pastures.* PhD Thesis, Palmerston North, Massey University, New Zealand.

Hetrick, B.A.D., Hetrick, J.A. and Bloom, J. 1984. Interaction of mycorrhizal infection, phosphorus level and moisture stress in growth of field corn. *Canadian Journal of Botany* 62:2267-2271.

Hewitt, A.E. 1998. *New Zealand Soil Classification*, second edition. Landcare Research, Dunedin, New Zealand:133.

Hira, G.S. and Singh, N.T. 1977. Observed and predicted rates of phosphorus diffusion in soil of varying bulk density and water content. *Soil Science Society of America Proceedings* 41:537-540

Jamieson, P.D. and Francis, G.S. 1991. Drought influence on maize dry matter production and grain yield in Canterbury. *Proceedings of the Agronomy Society of New Zealand*: 21-37.

Jamieson, P.D., Martin, R.J. and Francis, G.S. 1995. Drought influences on grain yield of barley, wheat and maize. *New Zealand Journal of Crop and Horticultural Science* 23:55-66.

Jensen, A. 1984. Responses of barley, pea and maize to inoculation with different vesicular-arbuscular mycorrhizal fungi in irradiated soil. *Plant and Soil* 78:315-323.

Jones, H.G. 1983. A quantitative approach to plant-environment interactions. In: *Plants and Microclimate.* Cambridge University Press, Cambridge, UK. p1-8.

Johnston, A.E. 2005. Phosphorus nutrition of arable crops. In: *Phosphorus: Agriculture and the Environment.* (Eds. J.T. Sims and A.N. Sharpley). ASA, CSSA and SSSA, Madison, Wisconsin, USA. p495-520.

Jugenheimer, R.W. 1976. *Corn: Improvement, Seed Production and Uses.* A Wiley-Interscience Publication, John Wiley & Sons, USA.

Jungk, A. 2001. Root hairs and the acquisition of plant nutrients from soil. *Journal of Plant Nutrition* and *Soil Science* 164:121-129.

Kamprath, E.J. and Watson, M.E. 1980. Conventional soil and tissue tests for assessing the phosphorus status of soils. In: *The Role of Phosphorus in Agriculture*. (Eds. F.E. Khasawneh, E.C. Sample and E.J. Kamprath). ASA, CSSA and SSSA, Madison, Wisconsin, USA. p433-464.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.S., Eash, N.S. and Jordahl, J.L. 1994. Long-term tillage effects on soil quality. *Soil & Tillage Research* 32:313-327.

Keeney, D.R. and Bremner, J.M. 1966. Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. *Agronomy Journal* 58:498-503

Khamis, S., Chaillou, S. and Lamaze, T. 1990. CO^2 assimilation and partitioning of carbon in maize plants deprived of orthophosphate. *Journal of Experimental Botany* 41:1619-1625.

Koske, R.E. and Gemma, J.N. 1989. A modified procedure for staining roots to detect VA mycorrhizas. *Mycological Research* 4:486-505.

Krishma, K.R. and Bagyaraj, D.J. 1981. Note on the effect of VA mucorrhiza and soluble phosphate fertiliser on sorghum. *Indian Journal of Agricultural Sciences* 51:688-690.

Krishma, K.R. and Dart, P.J. 1984. Effect of mycorrhiza inoculation and and soluble phosphorus fertiliser on growth and phosphorus uptake of pearl millet. *Plant and Soil* 81:247-256.

Kuchenbuch, R.O. and Barber, S.A. 1988. Significance of temperature and precipitation for maize root distribution in the field. *Plant and Soil* 106:9-14.

Kuchenbuch, R. and Jung, J. 1988. Changes in root-shoot ratio and ion uptake of maize (*Zea mays* L.) from soil as influenced by plant growth regulator. *Plant and Soil* 109:151-157.

Leonard, E. 2001. Controlled traffic farming. *The Furrow*. John Deere Publications. Australia. 1:14-15.

Logsdon, S.D. and Allmaras, R.R. 1991. Maize and soybean root clustering as indicated by root mapping. *Plant and Soil* 131:169-176.

Lynch, J.P. 1995. Root architecture and plant productivity. *Plant physiology* 109:7-13.

Lynch, J.P. and Brown, K.M. 2001. Topsoil foraging-an architectural adaptation of plants to low phosphorus availability. *Plant and Soil* 237:225-237.

Mackay, A.D. and Barber, S.A. 1985. Soil moisture effects on root growth and phosphorus uptake by corn. *Agronomy Journal* 77:519-523.

Major, D.J. and Hamilton, R.I. 1978. Adaptation of corn for whole plant stage in Canada. *Canadian Journal of Plant Science* 58:643-650.

Marschner, H. 1986. Mineral nutrient and yield response. In: *Mineral Nutrition in Higher Plants.* (Ed. M. Horst). Academic Press, Orlando, Florida, USA. p184-196.

Marschner, H. 1995. Functions of mineral nutrients: macronutrients. In: *Mineral Nutrition in Higher Plants*. (Ed. M. Horst). Academic Press, London. p229-299.

Marsh, B. 1971. Measurements of length in random arrangements of lines. *Journal of Applied Ecology* 8:265-267.

Matthew, C. 1992. *A study of seasonal root and tillar dynamics in swards of perennial ryegrass (Lolium perenne L.)* PhD Thesis, Palmerston North, Massey University, New Zealand.

Matthew, C., Mackey, A.D. and Chu, A.C.P. 1986. Techniques for measuring the root growth of a perennial ryegrass (*Lolium perenne* L.) pasture under contrasting spring managements. *Proceedings of the Agronomy Society of New Zealand* 16:59-64.

McKenzie, H.A. and Wallace, H.S., 1954. The Kjeldahl determination of nitrogen. A critical study of digestion condition-temperature, catalyst and oxidizing agent. *Australian Journal of Chemistry* 7:55-70.

McLaren, R.G. and Cameron, K.C. 1990. *Soil Science. An Introduction to the Properties and Management of New Zealand Soils*. Oxford University Press. New Zealand.

McLaren, R.G. and Cameron, K.C. 1996. *Soil Science. Sustainable Production and Environmental Protection.* 2nd edition. Oxford University Press. New Zealand.

McLean, E.O. 1977. Fertiliser and Lime recommendations based on soil tests. *Communications in Soil Science and Plant Analysis* 8:441-464.

Mengel, D.B. and Barber, S.A. 1974. Rate of nutrient uptake per unit of corn root system under field conditions. *Agronomy Journal* 66:341-344.

Mengel, K and Kirkby, E.A. 1987. Phosphorus. In: *Principles of Plant Nutrtion.* 4th edition. International Potash Institute, Worblaufen-Berne, Switzerland. p403-420.

Moir, J.L., Scotter, D.R., Hedley, M.J., Mackey, A.D., Tillman, R.W., Turner, M.A. and Horne, D.J. 2000b. Adding value to soil fertility- pasture growth relationships with a water balance. In: Proceedings of workshop *Soil Research: A knowledge industry for land- based exporters.* (Eds. L.D. Currie, and P. Loganathan). Occasional report No 13, FLRC, Massey University, Palmerston North. New Zealand. p225-239.

Moir, J.L., Scotter, D.R., Hedley, M.J. and Mackey, A.D. 2000a. A climatic-driven, soil fertility dependent, pasture production model. *New Zealand Journal of Agricultural Research* 43:491-500.

Moller Nielson, J. 1980. Evaluation of nutritional status of cereals. VI Trophogenesis. *Plant and Soil* 55:465-483.

Mollier, A. and Pellerin, S. 1999. Maize root system growth and development as influenced by phosphorus deficiency. *Journal of Experimental Botany* 50 (333): 487-497.

Morton, J., Craighead, M. and Stevenson, K. 2000. *Managing Soil Fertility on Cropping Farm*. New Zealand Fertiliser Manufacturers Research Association (NZFMRA), New Zealand.

Muchow, R.C., Sinclair, T.R. and Bennett, J.M. 1990. Temperature and solar radiation effects on potential maize yield across locations. *Agronomy Journal* 82:338-343.

Munir, S. 2000. *Effect of cultivation on maize response to nitrogen fertilizer.* M. Appl. Sc., Thesis. Massey University, Palmerston North, New Zealand.

Murphy, J. and Riley, J.P. 1962. A modified single solution method for determination of phosphate in neutral waters. *Analytica Chimica Acta* 27:31-36.

McNaughton, K.G., Clothier, B.E. and Kerr, J.P. 1979. Evaporation from land surfaces. In: *Physical Hydrology New Zealand Experience.* (Eds. D.L. Murray and P. Ackroyd). Toebes memorial volume:97-119.

Narayanan, A. and Reddy, B.K. 1982. Effect of phosphorus deficiency on the form of plant root system. In: *Plant Nutrition Proceedings of 9th International Plant Nutrition Colloquim,* volume 2. (Ed. A. Scaife). Warwick University, England. p412-417

Nel, P.C., Barnard, R.O., Steynberg, R.E., de Beer, J.M. and Groeneveld, H.T. 1996. Trends in maize grain yields in a long-term fertilizer trial. *Field Crops Research* 47:53-64.

New Zealand Meteorological Service. 1983. Summaries of climatological observations to 1980. *New Zealand Meterological Service Miscelaneous Publication* 177, Wellington. p74-75.

New Zealand Horticulture Facts & Figures. 2003. HortResearch. Palmerston North, New Zealand. p6-8.

NZ Soil Bureau. 1968. Soils of New Zealand. Part 1. Bulletin 26 (1):8-11.

Newman, E.I. 1966. A method of estimating the total length of root in a sample. *Journal of Applied Ecology* 3:139-145.

Nicoullaud, B., King, D. and Tardieu, F. 1994. Vertical distribution of maize roots in relation to permanent soil characteristics. *Plant and Soil* 159:245-254.

Nye, P.H. and Tinker, P.B. 1977. Local movement of solutes in soils. *Solute Movement in the Soil-root System*. (Eds. P.H. Nye and P.B. Tinker). Blackwell scientific publications. Oxford, London. p69-187.

Olsen, S.R., Cole, V.V., Watauable, F.S. and Dean, L.A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *United States Department of Agriculture Circular No* 939:1-9.

Olsen, S.R., Watanabe, F.S. and Danielson, R.E. 1961. Phosphorus absorption by corn roots as affected by moisture and phosphorus concentration. *Soil Science Society of America Proceedings* 25:289-294.

Olsen, S.R., Kemper, W.D., and van Schaik, J.C. 1965. Self diffusion coefficients of phosphorus in soil measured by transcient and steady-state methods. *Soil Science Society of America Proceedings* 29:154-158.

Ortiz-Monasterio, J.I., Pena, R.J., Pfeiffer, W.H. and Hede, A.H. 2002. Phosphorus use efficiency and durum wheat under irrigated conditions. In: *Proceeding of the 5th International Triticale Symposium* (Annex June 30-July 5). Poland. p9-14.

Pages, L., Jordan, M.O. and Picard, D. 1989. A simulation model of the three dimensional architecture of the maize root system. *Plant and Soil* 119:147-154.

Pages, L. and Pellerin, S. 1994. Evaluation of parameters decribing the root system architecture of field grown maize plants (*Zea mays* L.). *Plant and Soil* 164:169-176.

Pellerin, S. and Pages, L. 1996. Evaluation in field conditions of a three-dimensional architectural model of the maize root system. Comparison of simulated and observed horizontal root maps. *Plant and Soil* 178:101-112.

Plenet, D., Etchebest, S., Mollier, A. and Pellerin, S. 2000a. Growth analysis of maize field crops under phosphorus deficiency. I. Leaf growth. *Plant and Soil* 223:117-130.

Plenet, D., Mollier, A. and Pellerin, S. 2000b. Growth analysis of maize field crops under phosphorus deficiency. II. Radiation-use efficiency, biomass accumulation and yield components. *Plant and Soil* 224:259-272.

Prasad, M., Spiers, T.M. and Ravenwood, I.C. 1988. Target phosphorus soil test values for vegetables. *New Zealand Journal of Experimental Agriculture* 16:83-90.

Pruitt, W.O. 1986. Traditional methods evapotranspiration research priorities for the next decade. *ASAE Paper No 86-2629*. 23.

Priestley, C.H.B. and Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review* 100:81-92.

Raju, P.S. 1986. *Vesicular-arbuscular mycorrhizal infection effects on growth and uptake of phosphorus and mineral elements by sorghum.* Ph.D. Thesis, University of Nebraska, Lincoln, USA.

Ragothama, K.G. 2005. Phosphorus and plant nutrition: An overview. In: *Phosphorus: Agriculture and the Environment.* (Eds. J.T. Sims and A.N. Sharpley). ASA, CSSA and SSSA, Madison, Wisconsin, USA. p355-378.

Rausch, C. and Bucher, M. 2002. Molecular mechanism of phosphate transport in plants. *Planta* 216:23-37.

Reid, J. B. 1981. Observations on root hair production by Lucerne, maize and perennial ryegrass grown in a sandy loam. *Plant and Soil* 62:319-322.

Reid, J.B. 2002. Yield response to nutrient supply across a wide range of conditions.1. Model derivation. *Field Crops Research* 77:161-171.

Reid, J. B. and Goss, M.J. 1982. Relationship between the decreases in soil stability effected by growth of maize roots and changes in organically bound iron and aluminium. *Journal of Soil Science* 33:397-410

Reid, J.B., Pearson, A.J. and Stone, P.J. 2001a. Land management for grain maize. Recommended best management practices for New Zealand. New Zealand Institute for Crop & Food Research, Hastings, New Zealand. p1-40.

Reid, J.B., Pearson, A.J. and Stone, P.J. 2001b. Land management for sweet corn. Recommended best management practices for New Zealand. New Zealand Institute for Crop & Food Research, Hastings, New Zealand. p1-48

Reid, J.B., Sorensen, I. and Petrie, R.A. 1993. Root demography in Kiwifruit (*Actinidia deliciosa*). *Plant Cell Environment* 16:949-957.

Reid, J.B., Stone, P.J., Pearson, A.J. and Wilson, D.R. 2002. Yield response to nutrient supply across a wide range of conditions.2. Analysis of maize yields. *Field Crops Research* 77:173-189.

Reid, J.B., Winfield, D., Sorensen, I., and Kale, A.J. 1996. Water deficit, root demography and the causes of internal blackening in field grown tomatoes (Lycopersicon esculentum Mill). *Annual Applied Biology* 129:137-149

Reid, J.B., Stone, P.J. and Pearson, A.J. 1999a. Quantifying the benefits of management practices. In: Proceedings of the workshop *Best soil management practices for production* (Eds. L.D. Currie, M.J. Hedley, D.J. Horne and P. Loganathan). Occasional report No 12. FLRC, Massey University, Palmerston North, New Zealand. p63-69.

Reid, J. B., Stone, P. J., Pearson, A. J., Cloughley, C., and Wilson, D. R. 1999b. 'The Maize Calculator' - a simple system for predicting fertiliser nitrogen requirements of maize. *Proceedings of Agronomy Society of New Zealand 29*:73-74.

Rhodes, H, L. and Gerdemann, W.J. 1975. Phosphate uptake zones of mycorrhizal and nonmycorrhizal onions. *New Phytologist* 75:555-561.

Rhodes, L.L. and Eagles. 1984. Origins of maize in New Zealand. *New Zealand Journal of Agricultural Research* 27:151-156.

Riley, M.M., Adcock, K.G. and Bolland, M.D.A. 1993. A small increase in the concentration of phosphorus in the sown seed increased the early growth of wheat. *Journal of Plant Nutrition* 16:851-864.

Ritchie, S.W. 1997. *How a corn plant develops. Special report No 48.* Iowa State University of Science and Technology Cooperative Extension services. p1-21.

Richardson, A.E., George, T.S., Hens, M. and Simpson, R.J. 2005. Utilization of soil organic phosphorus by higher plants. In: *Organic Phosphorus in the Environment* (Eds. B.L. Turner, E. Frossard and D.S. Baldwin). CAB International Publication, USA. p165-185.

Robins, J.S. and Domingo, C.E. 1953. Some effects of severe soil moisture deficits at specific growth stage in corn. *Agronomy Journal* 45:612-621.

Rosolem, C.A., Assis, J.S. and Santiago, A.D. 1994. Root growth and mineral nutrition of corn hybrids as affected by phosphorus and lime. *Communications in Soil Science and Plant Analysis* 25:2491-2499.

Sanchez, C.A., Porter, P.S. and Ulloa, M.F. 1991. Relative efficiency of broadcast and banded phosphorus for sweet corn produced on Histosols. *Soil Science Society of America Journal* 55:871-875.

SAS® version 8.2. 1999-2001. SAS Institute Inc, Cary, North Carolina, USA.

Sayer, S.T. 1991. Fusarium infection in some Waikato maize. *New Zealand Journal of Crop and Horticultural Science* 19:149-155.

Sayre, J.D. 1948. Mineral accumulation in corn. *Plant physiology* 23:267-281.

Sayre, J.D. 1955. *Mineral Nutrition of Corn.* Academic Press, New York, USA.

Schenk, M.K. and Barber, S.A. 1979. Root characteristics of corn genotypes as related to P uptake. *Agronomy Journal* 71:921-924.

Schenk, M.K. and Barber, S.A. 1980. Potassium and phosphorus uptake by corn genotypes grown in the field as influenced by root characteristics. *Plant and Soil* 54:65-76.

Scotter, D.R., Clothier, B.E. and Turner, M.A. 1979. The soil water balance in a fragiaqualf and its effect on pasture growth in central New Zealand. *Australian Journal of Soil Research* 17:455-465.

Scotter, D.R. 1996. Communication: 89.211: *Study Guide 3. Soil Science*. Massey University, Palmerston North, New Zealand.

Scotter, D.R., Horne, D.J., and Green, S.R. 2000. A procedure for generating daily rainfall and evaporation data. An evaluation and some application. *Journal of Hydrology (NZ)* 39:65-82.

Scotter, D. and Heng, L. 2003. Estimating reference crop evapotranspiration in New Zealand. *Journal of Hydrology (NZ)* 42:1-10.

Shaw, R.H. 1977. Climatic requirements. In: *Corn and Corn Improvements*. (Eds. G.F. Sprague, D.A. Fuceillo, L.S. Perelman and M. Stelly). ASA, Madison, Wisconsin, USA. p18-20.

Silberbush, M. and Barber, S.A. 1983. Sensitivity of simulated phosphorus uptake to parameters used by a mechanistic mathematical model. *Plant and Soil* 74:93-100.

Simpson, J.R. and Pinkerton, A. 1989. Fluctuations of soil moisture and plant uptake of surface applied phosphate. *Fertiliser Research* 20:101-108.

Sigunga, D.O., Janssen, B.H. and Oenema, O. 2002. Effects of improved drainage and nitrogen source on yields, nutrient uptake and utilization efficiencies by maize (*Zea Mays* L.) on Vertisols in sub-humid environments. *Nutrient Cycling in Agroecosystems* 62:263-275.

Smith, S.E. 1980. Mycorrhizas of autotrophic higher plants. *Biological Reviews* 55:475-510.

Smith, S.E. and Pearson, V.G. 1988. Physiological interactions between symbionts in vesicular-arbuscular mycorrhizal plants. *Annual Review of Plant Physiology* 39:221-244.

Smucker, A.J.M., McBurney, S.L. and Srivastava, A.K. 1982. Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. *Agronomy Journal* 74:500-503.

Snyder, R.L., Lanini, B.J., Shaw, D.A. and Pruitt, W.O. 1989. Using reference evapotranspiration (ET_O) and crop coefficients to estimate crop evaporation (ET_C) for agronomic crops, grasses and vegetable crops. Cooperative Extension, University California, Berkeley, California, Leaflet No. 21427. p12.

Steele, K.W. 1981. Maize Fertilizers. Estimating nitrogen fertilizer requirements. N.Z. Aglink FPP602. MAF. p2.

Steele, K.W. 1983. Efficient utilization of soil and fertilizer N to optimize maize grain yield. *Proceedings of the Agronomy Society of New Zealand* 13:33-38.

Steele, K.W. 1985. Fertiliser management for grain maize. In: *Maize Management to Market* (Eds. H.A. Eagles and G.S. Wratt). Agronomy Society of New Zealand. Christchurch, New Zealand. Special Publication No. 4:29-36.

Steele, K.W. and Cooper, D.M.1980. Reducing fertiliser applications to maize. *Proceedings of Ruakura Farmers Conference*:25-34.

Steele, K.W., Cooper, D.M. and Dyson, C.B. 1982. Estimating nitrogen fertilizer requirements in maize grain production. I. Determination of available soil nitrogen and prediction of grain yield increase to applied nitrogen. *New Zealand Journal of Agricultural Research* 25:199-206.

Steele, K.W., McCormick, S.J., Percival, N. and Brown, N.S. 1981. Nitrogen, phosphorus, potassium, magnesium and sulphur requirements for maize grain production. *New Zealand Journal of Experimental Agriculture* 9:243-249.

Stevenson, F.J. and Cole, M.A. 1999. The phosphorus cycles. In: *Cycles of Soil. Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients.* (Eds. F.J. Stevenson and M.A. Cole). Second edition. Publisher, John Wiley & Sons, Inc. New York, USA. p279-324.

Stewart, W.B. and Chauhan, B.S. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and laboratory incubation. *Soil Science Society of America Journal* 46:970-976.

Stone, P.J., Sorensen, I.B. and Jamieson, P.D. 1999. Effect of soil temperature on phenology, canopy development, biomass and yield of maize in a cool-temperate climatic. *Field Crops Research* 63:169-178.

Stone, P.J., Wilson, D.R., Reid, J.B. and Gillespie, R.N. 2001. Water deficit effects on sweet corn. 1. water use, radiation use efficiency, growth and yield. *Australia Journal of Agricultural Research* 52:103-113.

Sumanasena, A.H. 2003. *A study of combined effects of irrigation, frequency and phosphorus fertility on summer pasture production.* PhD Thesis, Massey University, Palmerston North, New Zealand.

Technicon, 1976. Technicon manual for ammonium analysis. Tarrytown, New York.

Tennant, D. 1975. A test of a modified line intersect method of estimating root length. *Journal of Ecology* 63:995-1002.

Thorup, R.M. 1969. Root development and P uptake by tomato plants under controlled soil moisture conditions. *Agronomy Journal* 61:808-811.

Thom, E.R. and Watkin, B.R. 1978. Effect of rate and time of fertilizer nitrogen application on total plant, shoot and root yields of maize (*Zea mays* L.). *New Zealand Journal of Experimental Agriculture* 6:29-38.

Tinker, P.B. 1978. Effects of vesicular-arbuscular mycorrhizae on plant growth. *Physiologie Vegetale* 16:743-751.

Tinker, P.B. and Nye, P.H. 2000. Local movements of solutes in soil. In: *Solute Movement in the Rhizosphere*. (Eds. P.B. Tinker and P.H. Nye). Oxford University Press. Oxford, UK. p71-129.

Toth, R., Page, T. and Castleberry, R. 1984. Differences in mycorrhizal colonization of maize selections for high and low ear leaf phosphorus. *Crop Science* 24:994-996.

Trolove, S.N., Hedley, M.J., Caradus, J.R. and Mackay, A.D. 1996. Uptake of phosphorus from different sources by Lotus pendunculatus and three genotypes of Trifolium repens. I. Plant yield and phosphate efficiency. *Australian Journal of Soil Research.* 34:1015-1026.

Trolove, S.N., Hedley, M.J., Kirk, G.J.D., Bolan, N.S. and Loganathan, P. 2003. Progress in selected areas of rhizosphere research on P acquisition. *Australian Journal of Soil Research* 41:471-499.

Unger, P.W. 1996. Soil bulk density, penetration resistance and hydraulic conductivity under controlled traffic conditions. *Soil and Tillage Research* 37:67-75.

Wallace, E. 1975. *New Zealand Vegetable Growers Handbook*. Henry H.Y and Co. Ltd. Petone, New Zealand.

Warneke, P.J. and Barber, S.A. 1974. Root development and nutrient uptake by corn grown in solution culture. *Agronomy Journal* 66:514-516.

Weaver, J.E. 1926. Root Habits of corn or maize. In: *Root Development of Field Crops.* (Ed. J.E. Weaver). McGraw-Hill Book Company, Inc, Publication. New York, USA. p181-273.

Westerman, R.L. 1990. *Soil Testing and Plant Analysis.* Book series No 3. SSSA, Madison, Wisconsin, USA. p784.

Wiesler, F. and Horst, W.J. 1993. Differences among maize cultivars in the utilization of soil nitrate and the related losses of nitrate through leaching. *Plant and Soil* 151:193-203.

Wiesler, F. and Horst, W.J. 1994. Root growth and nitrate utilisation of maize cultivars under field conditions. *Plant and Soil* 163:277-277.

Wilson, D.R., Muchow, R.C. and Murgatroyd, C.J. 1995. Model analysis of temperature and solar radiation limitations to maize potential productivity in a cool climatic. *Field Crops Research* 43:1-18.

Williams, P.H. 1998. Future nutrient requirements of arable and vegetable crops. In: Proceedings of the workshop *Long-Term Nutrient Needs For New Zealand's Primary Industries.* (Eds. L.D. Currie and P. Loganathan). Occasional Report No.11. FLRC, Massey University, Palmerston North, New Zealand. p55-66.

Wolfe, D.W., Azanza, F. and Juvik, J.A. 1997. Sweet corn. In: *The Physiology of Vegetable Crops* (Ed. H.C Wien). CAB International. UK. p461-478.

Wolfe, D.W., Henderson, D.W., Hsiao, T.C. and Alvino, A. 1988. Interactive water and nitrogen effects on senescence of maize. I. Leaf area duration, nitrogen distribution and yield. *Agronomy Journal* 80:859-864.

Woodward, S.J.R., Baker, D.J., and Zyskowski, R.F. 2001. A practical model for predicting soil water deficit in New Zealand pastures. *New Zealand Journal of Agricultural Research* 44:91-109.

Wright, A. and Barrs, J.A. 1976. A simulation model of grazing system with particular reference to soil-plant- climate relationships. In: *Symposium on Meteorology and Food Production*, (Ed. J.F. De Lisle) New Zealand Meteorological Services, Wellington, New Zealand. p183-196.

Wright, J.L. 1981. Crop coefficients for estimates of daily crop evapotranspiration. *Irrigration Scheduling for Water and Energy Conservation in the 80s*, ASAE, December 1981.

Wu, P., Dai, Q., and Tao, Q. 1993. Effect of fertiliser rates on the growth, yield and kernel composition of sweet corn. *Communications in Soil Science and Plant Analysis* 24:237-253.

Wu, L., McGechan, M.B., Watson, C.A. and Baddeley, J.A. 2005. Developing existing plant root system architecture models to meet future agricultural challenges. In: *Advances in Agronomy* 85. (Ed. D.L. Sparks). A Elsevier Academic Publication, USA. p181-219.

Zhang, J. and Barber, S.A. 1992. Maize root distribution between phosphorus-fertilised and unfertilized soil. *Soil Science Society of America Journal* 56:819-822.

Zoysa, A.K.N. 1997. *The influence of phosphorus fertiliser forms and rhizosphere processes on the phosphorus nutrition of tea (Camellia sinensis L.)*. PhD Thesis, Massey University, Palmerston North, New Zealand.

Zoysa, A.K.N., Loganathan, P. and Hedley, M.J. 1999. Phosphorus utilization efficiency and depletion of phosphate fractions in the rhizosphere of three tea (*Camellia sinensis* L.) clones. *Nutrient Cycling in Agroecosystems* 53:189-201.

Zuber, M.S. and Darrah, L.L. 1987. Breeding, genetics and seed corn production. In: *Corn: Chemistry and Technology* (Eds. S.A. Watson and P.E Ramstad). Amercian Association of Cereal Chemists, Inc., St Paul, Minnesota, USA. p31-47.

APPENDICES

Appendix 3.1 Soil texture classifications of Hawke's Bay experiment site at 14 DAS.

Soil Depths (mm)	Soil Texture classifications		Approximate composition
	Maize	Sweet corn	
150-250	Clay loam	Clay loam	35 % clay, 35 % sand and 30 % silt
280-320	Clay loam	Clay loam	
380-420	Sandy	Sand loam	
580-620	Loamy sand	Loamy sand	
780-820	Loamy sand	Loamy sand	70 % sand, 10 % silt and 10 % clay
980-1002	Loamy sand	Loamy sand	

Appendix 3.2a Soil bulk density and porosity in the Hawke's Bay experiment site at 37 DAS.

Soil Depth (mm)	Soil bulk density (g/cm^3) and soil Porosity (f) (%)											
	Maize						Sweet corn					
	0 kg P/ha		100 kg P/ ha		200 kg P/ ha		0 kg P/ ha		100 kg P/ ha		200 kg P/ ha	
	BD (g/cm^3)	f (%)	BD (g/cm^3)	f (%)	BD (g/cm^3)	f (%)	BD (g/cm^3)	f (%)	BD (g/cm^3)	f (%)	BD (g/cm^3)	f (%)
0-75	-	-	0.98	63	0.93	65	0.88	67	-	-	0.88	67
150	-	-	1.02	62	0.99	62	0.94	65	-	-	0.98	63
300	-	-	1.02	62	0.93	65	0.98	63	-	-	0.76	71
400	-	-	0.52	80	0.60	77	0.70	74	-	-	0.57	78

values with 200 kg P/ ha are mean for 2 replicates, whereas with 0 and 100 kg P/ ha are single replicate

Appendix 3.2b Soil bulk density and porosity in the Manawatu experiment site at 45 DAS.

Soil depths (mm)	Soil bulk density (g/cm^3) and soil Porosity (f) (%)			
	Maize		Sweet corn	
	BD (g/cm^3)	f (%)	BD (g/cm^3)	f (%)
0-100	0.99	63	0.93	65
100-200	1.17	56	1.10	58
200-300	1.28	51	1.31	51
300-400	1.30	51	1.33	50

values in columns are mean for 2 replicates from control treartments

Appendix 3.3a Maize (hybrid 34E79) and sweet corn (hybrid Challenger) partitioning of dry matter yield (t/ha) at 75 DAS (28.1.2002) in the Hawke's Bay experiment (2001-02)

Treatment P rate (kg/ ha)	Dry matter yield (t/ ha)													
	Leaf (1-6)		Leaf (7-12)		Leaf (13-18)		Stem with tassel		Tiller		Cob with husk		TDM	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	.14 a	.07 a	1.93 a	1.33 a	1.04 a	1.19 a	7.40 a	5.10 a	.06 a	.46 a	00	.82 a	10.6 a	8.9 a
100	.21 a	.08 a	2.11 a	1.42a	1.02 a	1.01 a	8.93 a	4.93 a	.13 a	.94 b	00	.94 a	12.4 a	9.3 a
200	.21a	.06 a	2.04 a	1.35a	1.02 a	1.12 a	7.42 a	4.53 a	.06 a	1.0 bc	00	1.1 a	10.8 a	9.3 a
Mean	.18 A	.07 B	2.0 A	1.4 B	1.0 A	1.1 A	7.9 A	4.8 B	.08 A	.83 B	00 A	.96 B	11.3A	9.2 B
$LSD_{(0.05)}$	0.04		0.11		0.30		0.93		0.23		0.21		1.2	
Significance														
cultivar	s		s		ns		s		s		s		s	
fertiliser	ns		ns		ns		ns		ns		ns		ns	
cult*fert	ns		ns		ns		ns		ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 3.3b Maize (hybrid 34E79) and sweet corn (hybrid Challenger) partitioning of dry matter yield (t/ha) at 100 DAS (25.2.2002) in the Hawke's Bay experiment (2001-02)

Treatment P rate (kg/ha)	Dry matter yield (t/ ha)													
	Leaf (4-9)		Leaf (10-15)		Leaf (16-21)		Stem with tassel		Tiller		Cob with husk		TDM	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	.75 a	.46 a	2.93 a	1.86 a	1.08 a	0.22 a	11.3 a	5.9 a	.00 a	.81 a	4.0 a	4.6 a	20.1 a	13.9 a
100	.84 a	.08 a	2.94 a	1.90 a	0.99 a	0.20 a	11.7 a	6.1 a	.06 a	.32 a	4.0 a	4.3 a	20.6 a	13.5 a
200	.83a	.06 a	2.91 a	1.95 a	0.93 a	0.14 a	12.3 a	6.7 a	.85 a	1.1 a	4.3 a	6.0 a	22.2 a	16.6 a
Mean	.80 A	.56 B	2.9 A	1.9 B	1.0 A	.19 B	11.8A	6.3 B	.30 A	.74 A	4.1 A	4.9 A	21 A	15 B
$LSD_{(0.05)}$	0.11		0. 20		0.17		1.4		0.66		1.1		2.5	
Significance														
cultivar	s		s		s		s		ns		ns		s	
fertiliser	ns		ns		ns		ns		ns		ns		ns	
cult*fert	ns		ns		ns		ns		ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 3.4a Maize (hybrid 36H36) and sweet corn (hybrid Challenger) partitioning of dry matter yield (t/ha) at 80 DAS (10.1.2003) in the Manawatu experiment (2002-03).

Treatments	Dry matter yield (t/ha)							
	Leaf (1-4)		Leaf (5-9)		Stem with tassel		TDM	
P rate (kg/ha)	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	0.48 a	0.23 a	1.44 a	0.54 a	1.08 a	0.45 a	2.98 a	1.22 a
15	0.44 a	0.27 a	1.18 b	0.45 a	0.91 a	0.45 a	2.54 a	1.22 a
70	0.47 a	0.28 a	1.43 a	0.55 a	0.97 a	0.53 a	2.66 a	1.36 a
Mean	0.46 A	0.26 B	1.35 A	0.51 B	1.00 A	0.50 B	2.72 A	1.25 B
$LSD_{(005)}$	-		-		-		-	
Significance								
cultivar	s		s		s		s	
fertiliser	ns		ns		ns		ns	
cult.*fert	ns		ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 3.4b Maize (hybrid 36H36) and sweet corn (hybrid Challenger) partitioning of dry matter yield (t/ha) at 110 DAS (10.2.2003) in the Manawatu experiment (2002-03).

Treatment P rate (kg/ha)	Dry Matter yield (t/ha)													
	Leaf (1-3)		Leaf (4-6)		Leaf 7-9)		Leaf (10-14)		Stem with tassel		Cob with husk		TDM	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	.48 a	.33 a	.97 a	.67 a	.87 a	.46 a	.58 a	.04 a	5.0 a	2.8 a	.89 a	1.2 a	8.9 a	5.5 a
15	.42 ab	.33 a	..94 a	.66 a	.92 a	.44 a	.50 b	.05 a	4.8 a	2.9 a	.74 a	1.3 a	8.3 a	5.7 a
70	.37 b	.34 a	.87 a	.70 a	.92 a	.59 a	.52 ab	.07 a	5.0 a	3.2 a	.95 a	1.5 a	8.6 a	6.5 a
Mean	.42 A	.33 B	.93 A	.68 B	.90 A	.50 B	.53 A	.05 B	4.9 A	2.9 B	.86 A	1.4 B	8.6 A	5.9 B
$LSD_{(0.05)}$	0.04		0.06		0.10		0.04		0.4		0.4		0.9	
Significance														
cultivar	s		s		s		s		s		s		s	
fertiliser	ns		ns		ns		ns		ns		ns		ns	
cult*fert	ns		ns		ns		ns		ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 3.4c Maize (hybrid 36H36) and sweet corn (hybrid Challenger) partitioning of dry matter yield (t/ha) at 140 DAS (12.3.2003) in the Manawatu experiment (2002-03).

Treatment P rate (kg/ha)	Dry matter yield (t/ha)													
	Leaf (1-3)		Leaf (4-6)		Leaf (7-9)		Leaf (10-14)		Stem with tassel		Cob with husk		TDM	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	.44 a	.36 a	.85 a	.71 a	.85 a	.45 a	.49 a	.02 a	5.1 a	3.5 a	7.5 a	5.7 a	15.1ab	10.7ab
15	.49 a	.33 a	.86 a	.66 a	.92 b	.45 a	.45 a	.03 a	4.9 ab	3.2 a	8.6 a	5.3 a	16.1 a	10.1 a
70	.36 b	.33 a	.80 a	.68 a	.82 a	.52 a	.46 a	.04 a	4.4 b	3.6 a	7.4 a	6.5 a	14.3b	11.7b
Mean	.43 A	.34 B	.84 A	.67 B	.86 A	.47 B	.47 A	.02 B	4.8 A	3.5 B	7.8 A	5.9 B	15.2A	10.9 B
$LSD_{(0.05)}$	0.04		0.05		0.04		0.04		0.29		0.72		0.9	
Significance									s					
cultivar	s		s		s		s		ns		s		s	
fertiliser	s		ns		ns		ns		s		ns		ns	
cult*fert	s		ns		ns		ns				s		s	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 3.5a Raw data for Harvest Index (grain yield/total dry matter) for the Hawke's Bay experiment

Replicate	O kg P/ha	100 kg P/ha	200 kg P/ha
1	0.48	0.42	0.47
2	0.46	0.50	0.44
3	0.43	0.48	0.49

Appendix 3.5b Raw data for Harvest Index (grain yield/total dry matter) for the Manawatu experiment

Replicate	O kg P/ha	100 kg P/ha	200 kg P/ha
1	0.45	0.46	0.49
2	0.49	0.46	0.49
3	0.45	0.46	0.48
4	0.48	0.48	0.46
5	0.46	0.48	0.50

Appendix 4.1a Maize (hybrid 34E79) and sweet corn (hybrid Challenger) P uptake (kg P/ha) at 33 DAS (17.12.2001) in the Hawke's Bay experiment (2001-02).

Treatment P rate (kg/ha)	P uptake (kg P/ha)					
	leaves		Stem		Total P uptake	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	.126 a	.063 a	.703 a	.390 a	.83 a	.45 a
100	.130 a	.070 a	.776 a	.413 a	.90 a	.48 a
200	.150 a	.076 a	.613 a	.580 a	.76 a	.65 a
Mean	0.14 A	0.07 B	0.70 A	0.46 B	0.83 A	0.53 B
$LSD_{(0.05)}$	.02		.21		.23	
Significance						
cultivar	s		s		s	
fertiliser	ns		ns		ns	
cult.*fert	ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 4.1b Maize (hybrid 34E79) and sweet corn (hybrid Challenger) P uptake (kg P/ha) at 75 DAS (28.1.2002) in the Hawke's Bay experiment (2001-02).

Treatment P rate (kg/ha)	P uptake (kg P/ha)													
	Leaf (1-6)		Leaf (7-12)		Leaf (13-18)		Stem with tassel		Tiller		Cob with husk		Total P uptake	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	.32 a	.12 a	4.74 a	3.53 a	2.88 a	3.55 a	13.5 a	7.62 a	.23 a	1.03 a	-	2.8 a	21.6 a	18.6 a
100	.52 a	.16 a	5.93 b	4.29 b	3.01 a	3.90 a	18.8 b	8.27 a	.38 a	2.62 b	-	3.2 ab	28.6 b	22.4 b
200	.50 a	.11 a	5.59bc	4.29bc	3.01 a	3.82 a	15.7ac	8.04 a	.27 a	3.11bc	-	3.9 b	25.0 c	23.4 b
Mean	.45 A	.13 B	5.4 A	4.0 B	3.0 A	3.8 A	15.9 A	7.9 B	.29 A	2.3 B	-	3.31	25.1A	21.4B
$LSD_{(0.05)}$	0.12		0.45		0.93		1.5		0.66		-		1.2	
Significance														
cultivar	s		s		ns		s		s		-		s	
fertiliser	ns		s		ns		s		s		s		s	
cult.*fert	ns		ns		ns		s		s		-		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 4.1c Maize (hybrid 34E79) and sweet corn (hybrid Challenger) P uptake (kg P/ha) at 100 DAS (25.2.2002) in the Hawke's Bay experiment (2001-02).

Treatment P rate (kg/ha)	P uptake (kg/ha)													
	Leaf (4-9)		Leaf (10-15)		Leaf (16-21)		Stem with tassel		Tiller		Cob with husk		Total P uptake	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	1.6 a	0.9 a	7.7 a	5.6 a	2.8 a	0.5 a	10.3 a	5.9 a	-	1.6 a	9.8 a	12.0 a	32 a	27 a
100	1.9 a	1.4 b	7.8 a	6.6 ab	2.6 a	0.6 a	13.9 b	8.3 ab	.18 a	0.7 b	10.4 a	12.1 a	37 ab	30 a
200	1.9 a	1.4 b	7.7 a	6.9 bc	2.6 a	0.4 a	15.6bc	9.2 bc	1.9 a	2.5 c	11.1 a	18.0 b	41 b	39 b
Mean	1.8 A	1.2 B	7.8 A	6.4 B	2.6 A	0.51B	13.3 A	7.8 B	.29 A	2.3 B	10.5A	14.0B	37 A	32 A
$LSD_{(0.05)}$	0.31		0.68		0.93		1.5		0.66		2.95		5.4	
Significance														
cultivar	s		s		ns		s		s		s		ns	
fertiliser	s		ns		ns		s		s		ns		s	
cult.*fert	ns		ns		ns		s		s		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 4.2a Maize (hybrid 36H36) and sweet corn (hybrid Challenger) P uptake (kg P/ha) at 80 DAS (12.1.2003) in the Manawatu experiment (2002-03).

P rate (kg/ha)	P uptake (kg P/ha)							
	Leaf (1-4)		Leaf (5-9)		Stem		Total P uptake	
	Maize	Sweet Corn	Maize	Sweet corn	Maize	Sweet Corn	Maize	Sweet corn
0	1.01 a	0.46 a	3.84 a	1.31 a	1.71 a	1.39 a	6.6 a	3.1 a
15	0.85 a	0.51 a	2.87 b	1.17 a	1.60 a	1.36 a	5.3 b	3.0 a
70	1.01 a	0.55 a	3.60 a b	1.39 a	1.81 a	1.59 a	6.4 a b	3.5 a
Mean	0.96 A	0.51 B	3.44 A	1.29 B	1.71 A	1.45 B	6.1 A	3.2 B
$LSD_{(0.05)}$	0.11		0.45		0.23		0.68	
Significance								
cultivar	s		s		s		s	
fertiliser	ns		s		ns		ns	
cult.*fert	ns		ns		ns		ns	

Means values within in rows (species) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 4.2b Maize (hybrid 36H36) and sweet corn (hybrid Challenger) P uptake (kg P/ha) at 110 DAS (12.2.2003) in the Manawatu experiment (2002-03).

Treatment P rate (kg/ ha)	P uptake (kg P/ha)													
	Leaf (1-3)		Leaf (4-6)		Leaf 7-9)		Leaf (10-14)		Stem with tassel		Cob with husk		Total P uptake	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	0.70 a	0.50 a	1.84 a	1.54 a	1.94 a	1.18 a	1.54 a	0.09 a	4.58 a	2.88 a	2.59 a	2.99 a	13.2 a	9.2 a
15	0.55 a	0.61 a	1.78 a	1.54 a	1.96 a	1.24 a	1.16 b	0.14 a	3.74 a	3.30 a	2.22 a	3.45 a	11.4 a	10.3 a
70	0.56 a	0.59 a	1.82 a	1.60 a	2.66 a	1.52 a	1.41ac	0.20 a	4.92ab	3.36 a	2.82 a	4.22 a	14.2 a	11.5 a
Mean	0.60A	0.56A	1.81A	1.56B	2.18A	1.31B	1.37A	0.14B	4.41A	3.18B	2.54A	3.55B	13 A	10 B
$LSD_{(0.05)}$	0.11		0.24		0.44		0.13		0.63		0.97		1.86	
Significance														
cultivar	ns		s		s		s		s		s		s	
fertiliser	ns		ns		ns		ns		ns		ns		ns	
cult*fert	ns		ns		ns		ns		ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P= 0.05)

Appendix 4.2c Maize (hybrid 36H36) and sweet corn (hybrid Challenger) P uptake (kg P/ha) at 140 DAS (12.3.2003) in the Manawatu experiment (2002-03).

Treatment P rate (kg/ha)	P uptake (kg P/ha)													
	Leaf (1-3)		Leaf (4-6)		Leaf (7-9)		Leaf (10-14)		Stem with tassel		Cob with husk		Total P uptake	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	0.41ab	0.42 a	1.05 a	1.12 a	1.19 a	0.69 a	0.69 a	0.02 a	1.54 a	1.52 a	12.93a	13.19a	18.0 a	17.0 a
15	0.57 a	0.31 a	1.25 a	1.01 a	1.30 a	0.77 a	0.64 a	0.04 a	1.46 a	1.51 a	14.11a	12.08a	19.6 a	15.8 a
70	0.31 b	0.35 a	0.93 a	1.14 a	1.11 a	0.94 a	0.64 a	0.06 a	1.14 a	1.64 a	13.68a	15.49a	18.0 a	19.8 a
Mean	0.43A	0.36A	1.09A	1.07A	1.20A	0.80B	0.65A	0.04B	1.56A	1.38A	13.59A	13.58A	18.5A	17.5A
$LSD_{(0.05)}$	0.12		0.19		0.15		0.10		0.31		2.0		2.4	
Significance														
cultivar	ns		ns		s		s		ns		ns		ns	
fertiliser	ns		ns		ns		ns		ns		ns		ns	
cult*fert	ns		ns		ns		ns		ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 4.3a Maize (hybrid 36H36) and sweet corn (hybrid Challenger) N uptake (kg N/ha) at 80 DAS (12.1.2003) in the Manawatu experiment (2002-03).

Treatments P rate (kg/ha)	N uptake (kg N/ha)							
	Leaf (1-4)		Leaf (5-9)		Stem		Total N uptake	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	17.5 a	8.2 a	44.9 a	18.2 a	22.7 a	13.9 a	85 a	40 a
15	15.8 a	9.1 a	35.6 b	16.6 a	19.7 a	13.6 a	71 b	39 a
70	17.0 a	9.4 a	41.7a b	18.4 a	21.6 a	15.8 a	80 a b	44 a
Mean	16.8 A	8.9 B	40.7 A	17.7 B	21.3 A	14.4 B	79 A	41 B
$LSD_{(0.05)}$	1.5		5.0		2.6		7.8	
Significance								
cultivar	s		s		s		s	
fertiliser	ns		ns		ns		ns	
cult.*fert	ns		ns		ns		ns	

Means values within in rows (species) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 4.3b Maize (hybrid 36H36) and sweet corn (hybrid Challenger) N uptake (kg N/ha) at 110 DAS (12.2.2003) in the Manawatu experiment (2002-03).

Treatment P rate (kg/ ha)	N uptake (kg N/ha)													
	Leaf (1-3)		Leaf (4-6)		Leaf 7-9)		Leaf (10-14)		Stem with tassel		Cob with husk		Total N uptake	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	11.1 a	7.0 a	24.7 a	18.2 a	22.8 a	14.3 a	16.1 a	1.2 a	51.6 a	32.2 a	18.5 a	24.9 a	145 a	98 a
15	8.7bc	7.9 a	24.4 a	19.0 a	23.7 a	14.8 a	13.2 b	1.6 a	45.2 a	36.9 a	16.5 a	27.9 a	132 a	108 a
70	8.2 c	7.8 a	23.2 a	19.8 a	23.2 a	17.8 a	14.5ab	2.1 a	54.0 a	35.9 a	20.0 a	34.0 a	143 a	117 a
Mean	9.3A	7.6 B	24.1A	19.0B	23.2A	15.6B	14.6A	1.6B	50.3A	35.0B	18.3A	28.9B	140A	108B
$LSD_{(0.05)}$	1.3		2.6		3.3		1.7		5.5		7.9		16.1	
Significance														
cultivar	s		s		s		s		s		s		s	
fertiliser	ns		ns		ns		ns		ns		ns		ns	
cult*fert	ns		ns		ns		ns		ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P= 0.05)

Appendix 4.3c Maize (hybrid 36H36) and sweet corn (hybrid Challenger) N uptake (kg N/ha) at 140 DAS (12.3.2003) in the Manawatu experiment (2002-03).

Treatment P rate (kg/ha)	N uptake (kg N/ha)													
	Leaf (1-3)		Leaf (4-6)		Leaf (7-9)		Leaf (10-14)		Stem with tassel		Cob with husk		Total N uptake	
	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn	Maize	Sweet corn
0	6.7 ab	6.3 a	14.9ab	14.1 a	16.0 a	9.9 a	9.3 a	0.30 a	32.2 a	21.6 a	97.2 a	108.4a	176 a	161 a
15	8.5 a	4.5 a	16.8 a	12.3 a	19.3 b	10.3 a	9.0 a	0.72 a	29.0 a	21.7 a	106.0a	95.4 a	189a	145 a
70	5.4 b	5.1 a	13.3 b	14.1 a	14.8ac	12.5b	8.8 a	1.02 a	27.2 a	23.6 a	99.4 a	121.3a	169 a	178a
Mean	6.8 A	5.3 B	15.0A	13.5A	16.7A	10.9B	9.0 A	0.68B	29.5A	22.3B	100.8A	108.4A	178 A	161 B
$LSD_{(005)}$	1.3		1.6		1.3		1.1		4.0		12.0		15	
Significance														
cultivar	s		ns		s		s		s		ns		s	
fertiliser	ns		ns		ns		ns		ns		ns		ns	
cult*fert	ns		ns		ns		ns		ns		ns		ns	

Means values within rows (cultivars) and in columns (treatments) followed by same letter show no significant differences (P=0.05)

Appendix 4.4a Raw data for P and N uptake by maize grain for Hawke's Bay experiment (182 DAS).

	P uptake (kg P/ha)			N uptake (kg N/ha)		
Replicates	O kg P/ha	100 kg P/ha	200 kg P/ha	O kg P/ha	100 kg P/ha	200 kg P/ha
1	35	28	35	252	221	212
2	31	23	37	203	216	220
3	28	35	32	204	237	229

Appendix 4.4b Raw data for P and N concentration (%) uptake by maize grain for Hawke's Bay experiment (182 DAS).

	P (%)			N (%)		
Replicates	O kg P/ha	100 kg P/ha	200 kg P/ha	O kg P/ha	100 kg P/ha	200 kg P/ha
1	.25	.23	.23	-	-	-
2	.23	.24	.21	-	-	-
3	.17	.18	.26	-	-	-

Appendix 4.4c Raw data for P and N uptake by maize grain for Manawatu experiment (200 DAS).

	P uptake (kg P/ha)			N uptake (kg N/ha)		
Replicates	O kg P/ha	100 kg P/ha	200 kg P/ha	O kg P/ha	100 kg P/ha	200 kg P/ha
1	20	22	16	131	211	184
2	23	17	21	209	229	202
3	17	20	22	170	207	232
4	18	23	17	187	228	175
5	19	18	27	216	222	230

Appendix 4.4d Raw data for P and N concentration (%) uptake by maize grain for Manawatu experiment (200 DAS).

	P (%)			N (%)		
Replicates	O kg P/ha	100 kg P/ha	200 kg P/ha	O kg P/ha	100 kg P/ha	200 kg P/ha
1	.24	.18	.14	2.0	2.1	1.9
2	.19	.13	.18	1.9	2.0	1.9
3	.18	.16	.17	2.1	1.8	2.2
4	.15	.18	.19	1.9	1.9	2.0
5	.14	.14	.13	2.0	1.9	1.9