

**AN EVALUATION OF THE FERTILISER
REQUIREMENTS OF CHICORY (*Cichorium intybus* var.
sativum) IN KWAZULU-NATAL, SOUTH AFRICA**

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School of Agricultural, Earth and Environmental Sciences

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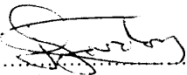
ABSTRACT

To assist with the development of fertiliser recommendations for root chicory (*Cichorium intybus* var. *sativum*), four irrigated field trials were conducted i.e., nitrogen (N) x phosphorus (P) x lime; N x potassium (K); boron (B); and acidity. A pot trial (K x soil type) was also carried out using five different soils. Yields were measured and leaf and root sampling conducted. Soils were fully analysed at the end of each field trial and after the pot trial. Leaf and root samples were also analysed. Non-exchangeable K and K adsorption isotherms were measured on the soils used in the pot trial. Root chicory responded favourably to N and root quality deteriorated when more than 180 kg N ha⁻¹ was applied. A soil phosphorus of 31 to 35 mg L⁻¹ was found to be sufficient. Soil K of 133 mg L⁻¹ achieved a yield of 43.27 t ha⁻¹ without the addition of N in the field trial. In the pot trial there was no significant response (p<0.05) to applied K as also found in the field trial. The pot trial showed that cognizance must be taken of clay percentage and type as root chicory responded significantly to different clay contents and probably within them to the different clay minerals present. Estimates of non-exchangeable K showed that all the soils had a K reserve that should be considered when soil fertiliser recommendations are made. The Freundlich adsorption isotherm allowed fertiliser requirements to be calculated for the different soils based on their initial adsorption capacity. Chicory responded positively to dolomitic lime, especially the calcium component, and tolerated high levels of lime (8 t ha⁻¹). Chicory did not respond significantly to boron either soil or foliar applied. However, it proved tolerant to relatively high levels of applied boron of up to 3.5 kg B ha⁻¹. The upper acid saturation percentage was not determined but results from the field trials showed that chicory was able to withstand levels of up to 25% with no detrimental effect on yield. It also appeared that root chicory was able to increase soil pH, thereby reducing aluminium solubility and toxicity.

DECLARATION

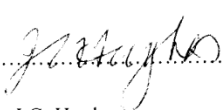
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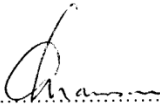
Date.....15/6/18.....

As the candidate's supervisors we have ~~both~~ approved this thesis for submission.

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Professor J.C. Hughes

Date.....15/6/18.....

Signed.....

Dr A.D. Manson

Date.....15/6/18.....

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CHAPTER ONE

INTRODUCTION

1.1 Preamble

The genus *Cichorium* (Asteraceae) consists of several species widely distributed through Europe and Asia (Bais and Ravishankar, 2001). In several Asteraceae, inulin, a β -2,1 linked fructose polymer with a terminal glucose residue, functions as a reserve carbohydrate in stems, tubers, and taproots (van Arkel et al., 2012). *Cichorium intybus* L., commonly known as chicory, is an erect fairly woody perennial herb, around 1m in height with a fleshy taproot of up to 75 cm in length and large basal leaves (Bais and Ravishankar, 2001). The name of the plant is derived from Greek and Latin. *Cichorium* means *field* and *intybus* is partly derived from the Greek “to cut”, because of the leaves, and partly from the Latin *tubus* to indicate the hollow stem (European Medicines Agency, 2013).

Historically, chicory was grown by the ancient Egyptians as a medicinal plant, coffee substitute and vegetable crop, and was occasionally used for animal forage. In the 1970s, it was discovered that the root of *Cichorium intybus* contained up to 40% inulin, which has a negligible impact on blood sugar and thus is suitable for diabetics (Judžentienė and Būdienė, 2008). Currently, *Cichorium intybus* is grown for the production of inulin on an industrial scale (van Arkel et al., 2012).

Chicory is a hardy plant and can endure extreme temperatures during both vegetative and reproductive growth stages (Bais and Ravishankar, 2001). When broken, all plant parts exude a milky latex (van Wyk et al., 1997). *Cichorium intybus* is cultivated for numerous applications and can be divided into four main varieties or cultigroups according to their use (Cadalen et al., 2010). These are (1) “industrial” or “root” chicory, predominantly cultivated in northwestern Europe, India, South Africa and Chile as a coffee substitute or for inulin extraction; (2) “Brussels” or “witloof” chicory is commonly cultivated in Europe for etiolated buds (chicons) by forcing; (3) “leaf” chicory is used as a fresh or cooked vegetable; and (4) “forage” chicory, initially derived from wild chicory commonly found along roadsides and waste areas, has been used since the mid-1970s to intensify herbage availability in perennial pastures for livestock.

1.2 Background and justification

Greyling (2010) reported that chicory is grown primarily as a dryland crop in South Africa with a mean wet yield of 20 t ha⁻¹. However, the yield and area planted to chicory reported by other sources (DAFF, 2013; FAOSTAT, 2013) differ from one another. On the one hand it is reported by FAOSTAT (2013) that the area planted in 2013 was 5 000 ha, with a mean wet yield of 5.66 t ha⁻¹ or approximately 28 300 t chicory. DAFF, (2013), on the other hand, does not report on the area but states that 28 734 t of dried chicory were produced during the 2011/12 season. There is a discrepancy in reporting as the FAOSTAT (2013) reports on wet yield while DAFF (2013) reports on dry yield (t yr⁻¹). Papetti et al. (2013) stated that 62 t ha⁻¹ (wet yield) was possible under favourable conditions. The differing yield levels indicate that there is a large variation, which requires clarification.

The Department of Agriculture and Rural Development (DARD) of KwaZulu-Natal (KZN) has embarked on a cooperative venture with Nestlé (South Africa) to produce root chicory for the Estcourt (176 km northwest of Durban: -29.01239° S ; 29.864163° E), KZN (Nestlé) factory as a supplement for their coffee product. The present poor quality of imported chicory from India and the depreciating Rand has influenced this decision to promote the production of chicory.

The objective of this venture is to give emerging growers the opportunity to grow chicory for a contract quota price. There are at present 21 identified producers and a small chicory processing plant at Weenen (207 km northwest of Durban: -28.83585° S ; 30.089631° E) in KZN. It is intended to increase this farming venture to the benefit of both Nestlé and the chicory producers, thereby expanding this to other farmers (including commercial farmers) in suitable parts of KZN.

Chicory for root production is a new crop in KZN, and fertiliser and management norms and standards are lacking. The current area of production which is focused around the towns of Weenen and Muden (174 km north northwest of Durban: -28.96666° S ; 30.383332° E) has a range of soil textures which makes the production of chicory challenging. Some of these challenges are the availability of registered weedicide products, correct fertiliser norms, climate and soil suitability requirements, cultivar choice, and time of planting.

The focus of this study was to address the limited knowledge regarding soil fertility, in KZN, using the fertiliser advisory programme (FERTREC) (Soil Fertility Section, Cedara, DARD-KZN) as a basis to establish fertility parameters for the crop.

Additionally, some of the soils in the Weenen/Muden area contain vermiculite-type 2:1 clays. From the literature it is evident that potassium (K) fixation can occur on these clay types (Miles, 1991; Farina et al., 1992; Farina et al., 1993; Johnston et al., 1999; Miles and Farina, 2014). There is a need to determine the K values at which point it is uneconomic to apply further K due to fixation by these clay types.

According to Manson and Roberts (2001) specific fertiliser calibration research for root chicory has not been done in KZN. Use has had to be made of literature studies from other parts of the world (Meijer and Mathijssen, 1992; Ćustić et al., 2002; Zobel et al., 2006) to provide suggested fertility guidelines which use different analytical methods for nutrient extraction. These studies do not reflect the Ambic-2/Hunter analytical extraction methods (as used by DARD in KZN) or the climatic and soil conditions that are experienced in KZN.

The potential knowledge benefit is seen as supplying much needed chicory fertiliser production parameters for the FERTREC. In addition, further understanding of K fixation on 2:1 vermiculitic clay soils will enhance K recommendations on these soil types. Along with the other current research projects at the Dundee Agricultural Research Station (DARS), KZN on chicory (forage chicory, weedicide/chicory and the anthelmintic properties of chicory) the present project will contribute to understanding the potential of this crop under the soil and climatic conditions prevalent in KZN. This study will ultimately help towards improving the yield of chicory and the gross margin for chicory farmers.

1.3 Objectives

The primary aim of the research was to provide quantitative data on chicory fertilisation for the DARD of KZN for incorporation into their FERTREC programme.

It is envisaged that the interpreted data will be used to provide norms for the fertilisation of chicory and be a reference for future soil fertility studies on root chicory in the Province. The objectives of this study were therefore to:

1. Determine and evaluate the nitrogen (N), phosphorus (P), K, and lime requirements for chicory root yield in KZN using the Ambic-2/Hunter analytical system of analysis.
2. Determine and evaluate the boron (B) requirements of chicory.
3. Determine and evaluate the acid saturation requirements of chicory.
4. Determine and evaluate possible K fixation of vermiculitic clays after applying six levels of K.
5. To use the data collected from the field experiments (1, 2 and 3) and pot experiment (4) to produce preliminary FERTREC guidelines for root chicory in KZN.

1.4 Structure of the thesis

The thesis is divided into five research areas each focusing on aspects of soil fertility. Four of these involve field trials and one a pot experiment.

Chapter 2 summarises the findings of international and local root chicory research. This has been accepted for publication in the Journal of Plant Nutrition with the title of " SOIL FERTILITY REQUIREMENTS OF ROOT CHICORY (*Cichorium intybus* var. *sativum*): A REVIEW" by D.H. Gordon, J.C. Hughes and A.D. Manson.

Chapter 3 focuses on the effect of N, P and lime interactions on the growth of chicory over a three-year field trial period where four levels of P, four levels of lime and four levels of N were applied on a sandy loam soil at DARS in KZN.

Chapter 4 describes the effect of N and K interaction on the growth of chicory over a three-year field trial period where five levels of K and four levels of N were investigated on at DARS.

Chapter 5 considers the effect of B on the growth of chicory using eight treatments split for soil and leaf treatments investigated in the field for two years at DARS.

Chapter 6 investigates the effect of soil acid saturation on the field growth of chicory using four liming rates and four N levels for two years at DARS.

Chapter 7 investigates the response of chicory to six levels of K fertilisation using five different soil types in a pot trial.

Chapter 8 discusses the applicability of the data to the FERTREC system and gives the overall conclusions of the work and suggestions for future work.

CHAPTER TWO

SOIL FERTILITY REQUIREMENTS OF ROOT CHICORY (*Cichorium intybus* var. *sativum*): A REVIEW

This has been accepted for publication in the Journal of Plant Nutrition with the authorship of D.H. Gordon, J.C. Hughes and A.D. Manson

2.1 Introduction

Chicory (*Cichorium intybus* L.) is a herb that has many uses including traditional uses such as phytochemistry, pharmacology and toxicology (Street et al., 2013). Chicory can be divided into four subgroups namely: 1) root chicory which is used mainly as a blend with coffee and is the focus of this review—this form is also increasingly being used for the production of inulin, 2) witloof chicory that is grown for its chicons through the forcing of an etiolated bud, 3) leafy chicory or salad chicory, and 4) forage chicory that was developed to provide high yielding forage for livestock.

The main countries that produce dried chicory root are India, South Africa, France, Belgium, the Netherlands and Poland (Table 2.1). The FAOSTAT (2013) data given in Table 2.1 do not list India as a chicory producing country. However, Patel et al. (2000) stated that India produced 30 000 t yr⁻¹ (1999 data) and would thus rank as the fourth highest chicory producer (later data for chicory production from India are unavailable). India exports a large proportion of its dried chicory to South Africa. Coffee is not grown in economically viable quantities in South Africa, and chicory is used with coffee in blends ranging from 25 to 75%, but on average 60% chicory is used. Pure chicory is also produced as an alternative to coffee (Minnaar, 1984).

Of all the countries where chicory is grown, South Africa is one of the few where it is grown solely for coffee purposes. European countries (particularly Belgium, the Netherlands and France) exploit the root for inulin and fructose syrups (Agriculture in South Africa, 1994; D'Egidio et al., 1998; IENICA, 2003). Inulin is a non-digestible carbohydrate; a fructan polymer consisting mainly of β (1→2) fructosyl fructose links. Enzymatic hydrolysis of inulin by inulinase results in the production, with a low degree of polymerisation, of oligosaccharides also called fructooligosaccharides (Smith and Wood, 1991; Druart et al., 2001; Ritsema and Smeekens, 2003). Inulin is used in the processed food industry and can

replace sugar, fat and flour and contains 25-30% of the food energy of carbohydrates (Roberfroid, 1999). It is also used industrially (e.g. in the production of ethanol) (Ohta et al., 1993), and in the medical field (e.g. colonic health) (Saad et al., 2013).

Table 2.1: Ranking of the top ten countries by fresh chicory root yield production and as a percentage of worldwide chicory root production and income (modified from FAOSTAT, 2013)

Ranking	Country#	World production (%)	Production (t)	Value (US\$* mill)
1	Belgium	53.9	269 515	30.31
2	France	17.7	88 323	9.93
3	Netherlands	11.0	57 000	6.41
4	South Africa	5.7	28 300	3.18
5	Poland	5.2	25 909	2.91
6	Puerto Rico	1.2	5 850	0.66
7	Serbia	1.0	5 000	0.56
8	Croatia	0.9	4 600	0.52
9	Philippines	0.8	3 800	0.43
10	Portugal	0.7	3 718	0.42
11	Other	1.9	6 194	0.70
World production			498 209	56.04

* US\$ 112.49 t⁻¹ (2014) received in South Africa

India data not available from FAOSTAT (2013)

As a result of the locations of the main areas that are planted, chicory is grown in soils with different properties, under various climatic conditions, and in both irrigated and dryland cropping systems. How the chicory crop performs under different fertility scenarios and in soils of varying textures requires evaluation so as to enable crop norms to be established. However, fertility guidelines for chicory are commonly based on norms derived from general recommendations (often for other crops) that are not necessarily based on quantitative research data. This is due mainly to the high cost of carrying out such research and the multitude of variables. A number of researchers have identified this tendency and have put forward algorithms to predict the crop responses (Greenwood et al., 1980 a,b,c; Lorenz, 1989; Alt and Rimmek, 1995; Feller and Fink, 2002). However, a model's calibration is often only pertinent to the area where it was developed. Model accuracy tends to decrease away from these centres, as larger variations tend to occur the wider the extrapolation.

Only limited information is available on the fertiliser requirements for root chicory, with some large variations in recommendations. Much of the international work has focused principally on nitrogen (N) and its effect on yield, with minimal work on the other important macro- and micronutrients and the influence of pH/liming/acidity/alkalinity (Sah et al., 1987; Crush and Evans, 1990). This review examines the work carried out on root chicory in terms of its fertilisation requirements with regard to macronutrients, some other nutrient elements and soil acidity.

2.2 Macronutrients

Table 2.2 summarises the field experiments carried out on root chicory to investigate response to N, phosphorus (P) and potassium (K). It is clear from Table 2.2 that (a) N has been the major focus and (b) much relevant information of the initial soil conditions that would allow more insight into the trials has not been reported. The discussion that follows highlights some of the major findings from these trials and from other related work on the N, P and K requirements for root chicory.

2.2.1 Nitrogen

In South Africa, Orchard and Van Rooyen (1953) applied 31 and 62 kg N ha⁻¹ under dryland conditions (Table 2.2). They found that although N significantly increased the yield of wet leaf, root yield was not significantly increased by application at the higher rate. Greyling (2010) suggested that N was not of great importance for root chicory and that only 50 kg N ha⁻¹ is required per season for an acceptable dryland yield of 20 t ha⁻¹. The current recommended application rate (for irrigation) in KwaZulu-Natal (KZN), South Africa ranges from 75 to 150 kg ha⁻¹ (following MAFF, 1988) depending on soil type.

Lachowski (1962) in Poland found that 120 kg N ha⁻¹ gave the highest root yield for the two chicory varieties researched. Sah et al. (1987) in California evaluated three crops under irrigation (fodder beet (*Beta vulgaris*), Jerusalem artichoke (*Helianthus tuberosus*) and grain sorghum (*Sorghum bicolor*)) in addition to chicory, for N utilisation and carbohydrate yield, as their main focus was on alcohol production. They found that chicory and fodder beet had the lowest N uptake rates and that they continued to take up N from soil for a longer period than the other crops. This suggests that chicory probably has a lower N requirement than the other crops.

The updated DEFRA (2010) fertiliser manual for the United Kingdom (UK) does not refer to chicory as was done in the past and therefore two other sources have been used namely MAFF (1988) and Red Tractor Farm Assurance (RTFA, 2010, 2015). MAFF (1988) in their recommended range between 75 and 150 kg N ha⁻¹ also distinguished between fen peats and “other soils”, with the former requiring a lower N application. Use has also been made of a N index based on the last crop grown to determine N needs. This range (0-150 kg N ha⁻¹) was revised downwards by RTFA (2010) to 0-75 kg N ha⁻¹. This was influenced by research by Dutch scientists who adopted deep soil sampling (0-90 cm) to determine mineral N. A number of other European countries have also adopted this technique. Application of 70 kg N ha⁻¹ and an assumed mean available soil N of 60 kg N ha⁻¹ for a total of 130 kg N ha⁻¹ was adopted in the UK by chicory producers (RTFA, 2010).

Améziane et al. (1997) investigated, in a pot trial, the effect of nitrate on photoassimilate (¹³C) partitioning within the plant. With low nitrate supply the shoot : root dry weight ratio decreased, which means that by manipulating the nitrate supply, carbon partitioning can be controlled to affect the dry matter production in leaves and tubers.

As fructans represents 80-85% of root dry weight (Limami and Fiala, 1993), the tubers themselves may be used in the sugar industry for the production of either inulin or fructose syrup following inulin hydrolysis. Possible ways of augmenting root sink activity are, therefore, of great interest. One established and effective way of doing this is through manipulation of the N supply to the plant (Rufty et al., 1984). Améziane et al. (1995) concurred that shoot growth of chicory plants during the vegetative period is much more affected by N supply than growth of the root. Supporting these findings, Van den Ende et al. (1999) in a pot trial, found that N played an important role in fructans and fructan-metabolizing enzymes.

Schittenhelm (1999) in a study, under irrigation, on the agronomic performance of root chicory, Jerusalem artichoke and sugar beet (*Beta vulgaris*) at Braunschweig, Germany, found that root chicory attained maximum yield with 60 kg N ha⁻¹. Root chicory attained peak sugar yields at medium N application rates as compared to sugar beet and Jerusalem artichoke which required a higher rate (120 kg N ha⁻¹).

Table 2.2: Summary of selected international field trials for nitrogen (N), phosphorus (P) and potassium (K) on root chicory. All were irrigated except Orchard and van Rooyen (1953)

Authors	Country	Soil texture	Initial pH	Initial A.S.* (%)	Initial P	Initial K	Mean residual N	N applied#	P applied#	K applied#
Orchard and Van Rooyen (1953)	South Africa	Sand	nr ^{\$}	nr	nr	nr	nr	31	14	No response to 39 and 78 applied
Lachowski (1962)	Poland	Silty loam	nr	nr	nr	nr	nr	120	28	133
Sah et al. (1987)	USA	Loam/fine silty	nr	nr	nr	nr	nr	100	26	50
Sah et al. (1987)	USA	Clay loam	nr	nr	nr	nr	nr	78	26	50
Patel et al. (1990)	India	Sandy loam	nr	nr	nr	nr	nr	nr	nr	nr
Baert and Van Bockstaele (1993)	Belgium	nr	nr	nr	nr	nr	nr	40	nr	nr
Alt et al. (1999)	Germany	Loamy sand	nr	nr	52	249	nr	-	35	190
Schittenhelm (1999)	Germany	Sandy loam	nr	nr	nr	nr	61	60	31	116
Patel et al. (2000)	India	Sandy loam	7.9	nr	27-35	206-229	3.3	100	No response	21
Wilson et al. (2004)	USA	Silt loam	7.9	nr	nr	nr	nr	145	nr	nr
Neuweiler et al. (2007)	Switzerland	Sandy loam	nr	nr	nr	nr	129	90	nr	nr
Khaghani (2012)	Iran	Loam	8.2	nr	nr	nr	nr	69	nr	nr
Moosavi (2012)	Iran	Loamy sand	8.1	nr	nr	nr	1.8	180	69	nr
Loaëc et al. (2014)	France	nr	nr	nr	nr	nr	116	30	nr	nr
Loaëc et al. (2014)	France	nr	nr	nr	nr	nr	144.5	30	nr	nr
Seghatoleslami et al. (2014)	Iran	Clay loam	8.1	nr	nr	nr	450 ppm	200	nr	nr
Gordon (2015; unpublished)	South Africa	Loamy sand	3.8 (KCl)	43	18	91	< 10	120-160	41	153

* A.S. – acid saturation

N, P and K applied for maximum yield

\$ nr – not reported

Patel et al. (2000) found that in the past there has been a large variation in the amount of N applied of between 50 and 200 kg ha⁻¹ on chicory lands in India. Their research work was done on a sandy loam, low in total N with a pH(H₂O) of 7.9 and a bulk density of 1.5 g cm⁻³. Their findings indicated that the fresh and dried root yields improved markedly with up to 100 kg N ha⁻¹ applied in two of the three seasons. However, in the combined analysis the yield differences were found to be non-significant when 50, 100, 150 and 200 kg N ha⁻¹ were applied.

Wilson et al. (2004) determined chicory root yield and carbohydrate composition in different cultivars, with different planting and harvest dates in Nebraska, under irrigation. The trials were situated on a Glenberg silt loam (Ustic Torrifuvent) with a pH(H₂O) of between 7.8 and 8.0 and an organic matter content between 0.8 and 1% following maize (*Zea mays* L.). The trial plots were brought up to a norm of 145 kg N ha⁻¹ by using urea-ammonium nitrate. However, the reason for this chosen level was not given. No P or K fertilisers were used in their experiment. Their findings suggested that planting date and cultivar selection were a significant factor in determining root yield and sugar content when fertilisation was “adequate”.

In earlier work, Chubey and Dorrell (1978) also found that the type of cultivar and the length of the growing season appeared to be the main factors which determined yield. Their studies suggested that irrigation and fertiliser application had little effect on the carbohydrate composition and root yields of chicory under low stress conditions, where good agronomic practices were followed and when the soil had “a good level of basic fertility”. However, as with Wilson et al. (2004) what was meant by the latter was not defined.

Baldini et al. (2006) investigated chicory and Jerusalem artichoke productivity in different areas of Italy, in relation to water availability and time of harvest. They used four sites for their research work (Udine, Rovigo, Cadriano and Policoro), and irrigation was evaluated as one of the production factors. Soil samples (chemical and textural) were taken at each site and fertilisation applied (Table 2.3). The N application was split-applied (pre-sowing and post-emergence).

Table 2.3: Yield of chicory at four sites in Italy with different initial soil properties and applied rates of nitrogen (N), phosphorus (P) and potassium (K) (modified from Baldini et al., 2006). For comparison, the values in brackets are those calculated from the Cedara Agricultural Research Station, KwaZulu-Natal recommendations using beetroot data as a proxy for chicory

Property	Udine	Rovigo	Cadriano	Policoro
Clay (%) (SD* g mL ⁻¹)	17(1.30)	43(≤1.00)	25(1.25)	23(1.25)
Organic matter (%)	2.9	2.2	1.3	3.6
Total N (%)	1.9	2.1	1.0	1.7
P (ppm) (mg L ⁻¹)	41(53)	11(11)	66(83)	27(34)
K (ppm) (mg L ⁻¹)	200(260)	116(116)	175(228)	227(284)
N applied (kg ha ⁻¹)	80(150)	130(150)	100(150)	150(150)
P applied (kg ha ⁻¹)	87(0)	35(119)	44(0)	52(29)
K applied (kg ha ⁻¹)	166(0)	157(85)	0(0)	0(0)
Wet yield (t ha ⁻¹)	33.9	54.0	65.6	46.5

* Sample density

They noted that rainfall and temperature had a significant effect on yield in addition to the fertiliser applied. Baldini et al. (2006), Wilson et al. (2004) and Chubey and Dorell (1978) emphasised cultivar choice, length of growing season and rainfall / irrigation as all playing a significant role in determining yield. Without consideration of these factors, fertiliser use by the plant would be sub-optimal. Baldini et al. (2006) used only 80 kg N ha⁻¹ at Udine on relatively low clay (17%) soil, and so leaching under irrigation would have been a factor in the lower yield as well as a low soil water retention capacity and the reported above mean temperatures. At the other three sites a higher amount of N was applied (100-150 kg ha⁻¹) with resultant increase in yield. The higher clay contents and likely higher water retention capacities probably limited the leaching of inorganic soil N from the rooting zone.

In a different climatic area to Baldini et al. (2006), Neuweiler et al. (2007) at Wadenswil Switzerland on a sandy loam under irrigation, with residual N of 129 kg ha⁻¹ established that for good quality roots under their environmental conditions 90 kg N ha⁻¹ was required in split applications, so that a total of 219 kg N ha⁻¹ was available for the plant. Residual N after the crop was harvested was not recorded, but if total removal was carried out according to Baert and van Bockstaele (1993) between 150 and 180 kg N ha⁻¹ would have been removed in the

roots and leaves. A residual amount of 39 to 69 kg N ha⁻¹ would have resulted, a decrease in available N from the initial amount (excluding any additions or removals from the N system).

Marinussen et al. (2012) summarised the work done in Europe on a number of macroelements and gave a “best estimate” of 70 kg N ha⁻¹ that was based to a large extent on the data of Schreuder et al. (2009) from their commercial budgeting analysis. Data from Eurostat (2012) cited Belgium as having an mean yield of 46.8 t ha⁻¹ and the Netherlands 42.7 t ha⁻¹ (two of the major chicory producing countries) from an mean annual application of 70 kg N ha⁻¹.

Khaghani et al. (2012) carried out fertiliser trial work under irrigation at Torbat Jam, Iran on root chicory on a loam soil with a pH(H₂O) of 8.2 in a hot, dry climate. Their findings from six treatments showed that the highest yield was obtained using urea (150 kg ha⁻¹) equivalent to 69 kg N ha⁻¹. Moosavi (2012) also in Iran, at Birjand, on an irrigated sandy loam found that 180 kg N ha⁻¹ gave the highest yield and that the root : leaf dry weight ratio decreased with increasing N application. Seghatoleslami et al. (2014) in work on chicory responses to N and plant density in Birjand, Iran, under irrigation, found that root chicory responded with a maximum yield at 200 kg N ha⁻¹ but its N utilisation efficiency (total dry yield/applied N, as defined by Bock, (1984)) declined with higher N treatments. In the climate of Iran on alkaline soils with textures ranging from a clay loam to a sandy loam a yield response to higher N applications is generally typical. Khaghani et al. (2012) used 69 kg N ha⁻¹ as their highest treatment. Probably if higher N treatments had been applied increasing yields would have resulted in line with Seghatoleslami et al. (2014) and Moosavi (2012). Residual inorganic N would be minimal in the soil, and little organic N will be mineralised, either from soil organic matter or crop residues, under these climatic conditions, hence the response to higher fertiliser N. The low residual N reported by Moosavi (2012) and Seghatoleslami (2014) (Table 2.2) supports this. Khaghani et al. (2012) do not report on this. In other warmer areas, Patel et al. (2000) in India found initial low residual N (0.30-0.34 g N kg⁻¹).

In contrast to the hot conditions in Iran and South Africa, under the cooler conditions of Europe there is a need to limit N leaching and the presence of residual N is assumed. This phenomenon is clearly illustrated by the amount of N applied by e.g. Neuweiler et al. (2007) and Loaëc et al. (2014) compared to Seghatoleslami et al. (2014) and Moosavi (2012). Environmental conditions are important to consider when extrapolating data from different regions and making decisions on N fertiliser rates.

Loaëc et al. (2014) in France (near Coutiches and Nomain) investigated the production of free asparagine, a major acrylamide precursor which is suspected to cause many health problems in humans (Lipworth et al., 2012), in response to N application. Asparagine is a commonly occurring natural amino acid and is required for the development and function of the brain (Ruzzo et al., 2013). A reaction between asparagine and reducing sugars or other source of carbonyls produces acrylamide in food when heated to sufficient temperature (Mottram et al., 2002; Tareke et al., 2002). These products occur in baked goods such as French fries, potato chips and toasted bread and have been reported to be possibly carcinogenic in humans (Mottram et al., 2002; Tareke et al., 2002). Roasted chicory is also known to be high in acrylamide (EFSA, 2012).

It was observed by Loaëc et al. (2014) that there was an increase in the content of free asparagines proportional to the amount of N added between 0 and 60 kg N ha⁻¹. Thereafter no significant difference in the amount of asparagines in cultivar roots was found up to the maximum applied of 120 kg N ha⁻¹. There was also a significant effect of N supply on the crude protein content which paralleled that observed for free asparagines. Maximum and minimum root yields were found when 30 kg N ha⁻¹ and 120 kg N ha⁻¹ were applied, respectively.

2.2.2 Phosphorus

In many situations, soil P and that supplied in fertiliser are largely unavailable for plants to utilise even under ideal soil conditions. Consequently, application rates of fertiliser P often exceed crop removals. Since leaching of P is minimal, except in some sandy soils, the inefficient utilisation of P fertilisers is problematic.

In South Africa (Eastern Cape Province) Orchard and Van Rooyen (1953) compared rates of 0, 14 and 28 kg P ha⁻¹. They found that P significantly increased root yield. The maximum P response was obtained from the lower dressing and there was no added advantage at the higher rate (Table 2.2). However, the initial soil P was not reported. In contrast, Greyling (2010) reported that a much higher application rate of between 60 and 80 kg P ha⁻¹ is required per season on sandy soil in the Eastern Cape chicory producing areas. Currently in KZN, a minimum “starter” dressing of 20 kg P ha⁻¹ is recommended for loam soils (sample density 1.25 g mL⁻¹) with 32-120 mg P L⁻¹ (Ambic-2 extractant), and a maximum of 88 kg P ha⁻¹ is

recommended for loams with less than 22 mg P L⁻¹ (Manson et al., 2012). If the soil P test is very high (>120 mg L⁻¹) then no application is recommended.

There is a lack of research on chicory utilisation of P except for Baert and van Bockstaele (1993) who state that chicory roots and leaves removed between 60 and 80 kg P₂O₅ ha⁻¹ (26.16 to 34.45 kg P ha⁻¹) from the soil with a wet yield of 57.5 t ha⁻¹.

Due to this lack of research on P fertility norms for root chicory, witloof chicory data have been used here to get an indication of fertility responses. In Germany at Osnabrück (Alt et al., 1999), long-term trials (nineteen harvests reported from a forty year-old trial) on vegetable crops, of which chicory (*var. foliosum*) was included (one harvest only), showed that nutrient removal per ton of edible plant parts was determined to be 0.49 kg P t⁻¹ with fertilisation of 35 kg P ha⁻¹. The annual amount of P removed by the edible plant parts averaged 22 kg P ha⁻¹. They regarded a soil with 8 to 12 mg P 100 g⁻¹ (80-120 mg P kg⁻¹) as adequate for maximum yield although the extractant method for P was not given.

In the UK, P application follows indexing classes according to soil analysis using the Olsen extraction. For soils other than fen peats, recommendations are 0, 11, 22, 44, 65 and 87 kg P ha⁻¹ for soils with >70, 46-70, 26-45, 16-25, 10-15 and 0-9 mg P L⁻¹, respectively (RTFA, 2010).

In India, Patel et al. (2000) found that P was beneficial in increasing root length and girth in all the seasons planted but there was no significant influence on the fresh and dry root yields. This lack of response was also reported previously (Patel et al., 1990) and was attributed to the high initial availability of P in the soil (between 27 and 35 kg P ha⁻¹) and the presumed low requirement of the crop.

Patel et al. (2000) also investigated the N x P interaction effect and found it to be significant for the dry root yield on a pooled basis. The treatment N₂P₁ (100 kg N and 50 kg P ha⁻¹) achieved the maximum dry root yield but it did not differ significantly from the yields given by the treatment combinations N₂P₀ (100 kg N and 0 kg P ha⁻¹) and N₄P₀ (200 kg N and 0 kg P ha⁻¹).

Baldini et al. (2006) applied P pre-sowing at their four sites (Table 2.3). The reasons for the fertilisation rates that were chosen are not evident as the quantitative research data for the

derivation are not referenced. However, it is known that more P is needed to raise the P test value in clay soils that have higher P-fixing capacities than sandy soils. It follows that more P fertiliser is required by clay soils than sandy ones for a unit increase in the soil P test (Miles, 1988; Johnston et al., 1991). The P requirement of a soil is the amount of P in kg ha^{-1} required to raise the soil test P value by 1 mg L^{-1} . This varies with the soil type, and is related to the sample density (Johnston et al., 1991). The sample densities are given in brackets in Table 2.3. Although the exact environmental details are not known, the applied P (from a KZN perspective) would be as shown in brackets (Table 2.3). All sites except the Rovigo site seem to be over-fertilised with P while Rovigo is under-fertilised.

In Europe, Marinussen et al. (2012) summarised the work done and made a “best estimate” for the P requirement of 8.7 kg ha^{-1} although this is much lower than the removal rates given by Baert and van Bockstaele (1993) of 26.16 to $34.45 \text{ kg P ha}^{-1}$.

2.2.3 Potassium

In South Africa, Orchard and Van Rooyen (1953) found that the two application rates of K used, namely 39 and 78 kg K ha^{-1} (Table 2.2) were not significantly different from each other as well as from a zero application for root yield at $p < 0.05$. The initial soil test value was, however, not given. High K application rates ranging between 150 and 180 kg K ha^{-1} per season are reported by Greyling (2010) to be necessary on the sandy soils of the Eastern Cape. Knowing that crop removals of K in roots can be high, and that the crop often responds to K applications, K fertiliser should be applied if the soil test is less than 200 mg K L^{-1} . No reference to texture has been suggested.

Lachowski (1962) found that 133 kg K ha^{-1} of mineral fertilisation gave the highest root yield for the two chicory varieties researched. Sah et al. (1987) used 50 kg K ha^{-1} as potassium chloride on their two irrigated trial sites in California. The basis for these values being chosen is not evident from their studies as initial soil sample results are not given.

Alt et al. (1999) from the long term trials at Osnabrück found that the annual removal of K by the edible plant parts averaged 190 kg ha^{-1} , with nutrient removal approximating 3.76 kg K t^{-1} with a fertilisation rate of 166 kg K ha^{-1} . Soil with between 8 and $16 \text{ mg K } 100\text{g}^{-1}$ ($80 - 160 \text{ mg K kg}^{-1}$) was regarded as being adequate for maximum yield for a number of vegetables,

including witloof chicory. Baert and van Bockstaele (1993) state that chicory roots and leaves remove between 240 and 300 kg K₂O ha⁻¹ (199.24 to 249.03 kg K ha⁻¹) from the soil.

Patel et al. (2000) found that the application of 21 kg K ha⁻¹ gave significantly more fresh and dry root yields than no application. The initial K varied between 206 and 229 kg ha⁻¹ which can be regarded as moderate according to the Cedara Agricultural Research Station, KZN norms (Manson et al., 2012). Patel et al. (1990) also found an increase in root yield with different K treatments but herbage yield was unaffected. Neither the interaction with N nor the initial K status of the soil is mentioned in their research findings.

MAFF (1988) suggested a range of 41 to 166 kg K ha⁻¹ depending on soil analysis. The latter was recommended for soils with ≤60 mg K L⁻¹ (ammonium nitrate extract) and the former for soils with between 241 and 400 mg K L⁻¹. Zero K was recommended for soils with greater than 400 mg K L⁻¹. Subsequent guidelines for the UK (RTFA, 2010; 2015) reduced these recommendations to 0, 21 and 125 kg K ha⁻¹ for the soil K ranges of >400, 241-400, and 0-60 mg K L⁻¹, respectively.

Witter and Johansson (2001) investigated the potential of using deep-rooted, green manure crops for K uptake from subsurface layers to increase available K in the cropping system. The research was undertaken near Uppsala in central Sweden, under dryland conditions. In cropping systems with shallow and deep-rooted crops they found that deep-rooted, green manure crops, such as chicory and lucerne (*Medicago sativa* L.), have the potential to extract and use subsoil K, which can subsequently be used by shallow-rooted crops after incorporation of the green manure. This suggests that subsoil K reserves may modify the chicory requirement for fertiliser K as has been found with K fertilisation of maize in KZN (Manson et al., 2012).

Baldini et al. (2006) applied K pre-sowing on their four sites (Table 2.3). The amounts of K applied at Udine and Rovigo were probably in excess of the requirements.

Marinussen et al. (2012) gave a “best estimate” K recommendation of 164 kg K ha⁻¹ based to a large extent on the work of Schreuder et al. (2009) and this seems a reasonable assumption considering the removal findings of Baert and van Bockstaele (1993).

2.3 Other nutrients

2.3.1 Calcium, magnesium, sulphur and micronutrients

No reports of calcium (Ca) fertiliser requirements could be found in the literature.

Alt et al. (1999) reported magnesium (Mg) removal by the crop to be 0.19 kg t^{-1} , with a fertilisation rate of 39 kg Mg ha^{-1} , equivalent to an average of $10.5 \text{ kg Mg ha}^{-1}$. They stated that Mg had no effect on yield. Soils with 50 mg Mg kg^{-1} were regarded as having sufficient Mg for maximum yield. There is very little research on plant utilisation except for Baert and van Bockstaele (1993) who found that chicory roots and leaves remove $50 \text{ kg CaO ha}^{-1}$ ($40.01 \text{ kg Ca ha}^{-1}$) and $20 \text{ kg MgO ha}^{-1}$ (12 kg Mg ha^{-1}) from the soil with a wet yield of 57.5 t ha^{-1} .

RTFA (2010) suggested application rates on sandy soils of 30 to $100 \text{ kg Mg ha}^{-1}$, whereas for “other soils” the recommendation ranged from 30 to 60 kg Mg ha^{-1} . These figures are only guidelines and are apparently not supported by quantitative data.

There is very little information on the use of sulphur (S) for root chicory except for Ali et al. (2013) in India who were interested in esculin production and Loaëc et al. (2014) in France. Esculin is found in the leaves of chicory (rather than the roots). It is important in the pharmaceutical industry (Buszewski et al., 1993) and is a glycosidic coumarin (monosaccharide of esculetin) belonging to a group of phenolic compounds distributed in natural plants (Anthoni et al., 2010). Ali et al. (2013) used 80 kg S ha^{-1} split into three amounts over the growing period, on a sandy loam soil under irrigation, and found that this split application enhanced esculin yield and was beneficial when applied before flowering along with 240 kg N , 120 kg P and 100 kg K ha^{-1} . The soil initially had a $\text{pH}(\text{H}_2\text{O})$ of 7.3 , an electrical conductivity (EC) of 0.33 dSm^{-1} , and 150 kg N , 4 kg P and 104 kg K ha^{-1} and was deficient in S.

Loaëc et al. (2014) suspected that a deficiency in S could lead to an increase in free asparagine and therefore an indirect increase in acrylamide in thermally processed foods after work done on potatoes by Muttucumaru et al. (2006; 2013). They applied three levels of liquid S (0 , 15 and 30 kg ha^{-1}) in a preliminary trial (var. *Orchies*), but found no significant

effect on free asparagine levels. However, the amount of S in the soil at the start of the experiment was not reported.

Root chicory utilisation of micronutrients has been little researched except for the work of Van Hee and Bockstaele (1983) in Belgium that showed that boron (B) deficiency leads to heart rot in the crown of the root and they recommend 1 kg B ha^{-1} as a preventative application. According to MAFF (1988), sodium (Na) can replace some but not all the K requirement and is beneficial to some crops (e.g. sugar beet) by increasing growth (El-Sheikh and Ulrich, 1970). Sugar beet, a comparable temperate root crop to chicory, is known to respond to Na application (MAFF, 1988) and it is possible that chicory could also benefit from the addition of Na. Baert and van Bockstaele (1993) have indicated that the roots and leaves of root chicory removed $15 \text{ kg Na}_2\text{O ha}^{-1}$ ($11.12 \text{ kg Na ha}^{-1}$) from the soil.

2.4 Acidity/pH/liming/alkalinity

Acidity is a critical yield-limiting factor in many soils, especially within the tropics and subtropics. About 40% of cultivated soils globally have acidity problems leading to significant decreases in crop production, despite adequate supply of mineral nutrients such as N, P and K (von Uexküll and Mutuert, 1995; Herrera-Estrella, 1999; Fageria and Baligar, 2008). Alkalinity is a condition that results from the accumulation of salts in the soil, and is characteristic of many arid and semiarid regions (Chhabra, 1996; Minhas and Sharma, 2003).

For South Africa no guide is given by Orchard and Van Rooyen (1953) or Greyling (2010) regarding the acceptable acidity levels required for root chicory. MAFF (1988) states that at a $\text{pH}(\text{H}_2\text{O}) < 5.1$ chicory yields will be detrimentally affected.

Upjohn and Michalk (1999) working with forage chicory in New South Wales, Australia used soil with a pH of 4.3(CaCl_2), low phosphorus (11 mg kg^{-1} Colwell P) and high aluminium saturation (41%) in a pot experiment to which the equivalent of 0, 0.5, 1.0, 1.5, 2.0 and 4.0 t ha^{-1} of agricultural lime was applied. They found that the change in soil $\text{pH}(\text{CaCl}_2)$ from pH 4.3 to 5.3 did not affect penetration of the chicory roots. It was found that the highest chicory yield was obtained at pH 4.4 (Figure 2.1). It was surmised that this was a result of a response to Ca as a nutrient. At higher lime application rates (1.0 to 4 t ha^{-1}) the yield reduction was in all likelihood attributable to a cation imbalance caused by high Ca concentrations and the shift in soil pH. These results showed that forage chicory is adapted to acid soils with a pH of

4.4. A pH(H₂O) of 6.0 was suggested by Baert and van Bockstaele (1993) for low clay soils, while pH 7.0 was recommended for heavier loam soils. They further recommended the application of 500 kg CaO ha⁻¹ yr⁻¹ preferably as a Mg-containing lime fertiliser. Marinussen et al. (2012) suggested a “best estimate” for lime of 400 kg ha⁻¹ which varied from 0 to 800 kg ha⁻¹, based as before on the work of Schreuder et al. (2009).

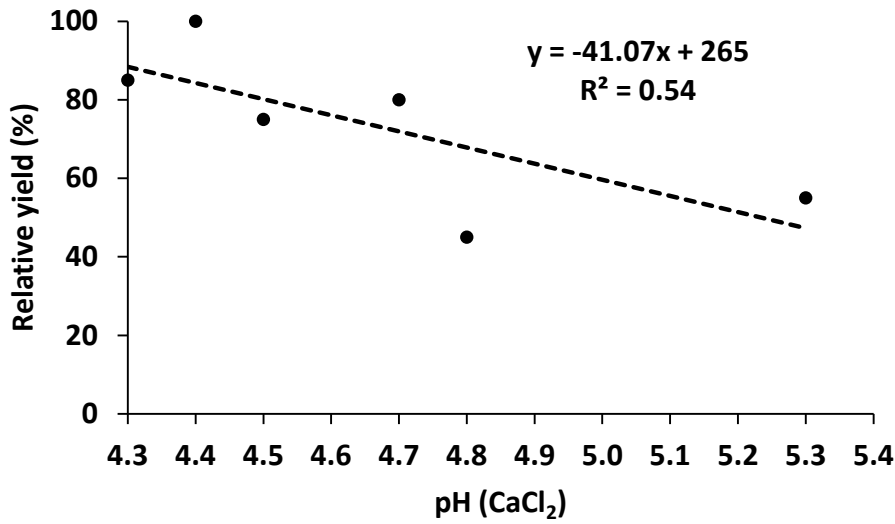


Figure 2.1: Forage chicory response to pH(CaCl₂) in soil surface after liming. Sub-surface pH = 4.3 (modified from Upjohn and Michalk, 1999).

2.5 Conclusion

Nitrogen has been well studied and the overall findings from the research suggest that root chicory does not have a high requirement for N. Indeed, high N fertiliser application has many negative connotations, from an increase in soft rot of the root to potential environmental concerns.

The amount of N in mineral soils is related to previous fertilisation, organic matter content and soil management practices such as irrigation. Therefore, the yield should be related to the total N used rather than only to the N fertiliser applied. However, the amount of soil N at the start of research work is not always stated, due partly to the difficulty in sampling and interpreting this value (Moll et al., 1982; Brown, 1987; Drinkwater et al., 1996; Manson et al., 2012). Chicory seems to be very effective in utilising soil N sources that may not be fully

available to other plants. The recommended rates vary from 30 to 200 kg N ha⁻¹. However, the general consensus for root chicory seems to favour a lower optimum rate between 30 and 120 kg N ha⁻¹. Some researchers, especially those investigating aspects of chicory research that are not primarily concerned with fertilisation, have not based their N fertilisation strategy on a quantitatively supported data source. Nitrogen interaction studies with other elements (e.g. N x K and N x P x lime) are very scarce.

Phosphorus response is indicated as minimal and many researchers report only limited benefit of applied P. However, it is evident that the initial soil data are given in only a few cases and it begs the question of the initial status of the trial site and the resultant P response. In addition, soil texture and pH/acid saturation are also often not reported making it difficult to determine target P levels. However, it is apparent that recommendations for chicory in general seem to be between 14 and 87 kg P ha⁻¹, with most researchers in favour of between 20 and 80 kg P ha⁻¹ for root chicory. Limited interaction trial work with P has been done.

Potassium research has not been extensive and recommended rates vary widely from 39 to 166 kg K ha⁻¹, with 75 to 150 kg ha⁻¹ the most favoured range. Soil texture and clay mineralogy and their relationship to K fertilisation are not well documented. Initial soil K has also received only very limited attention which may be related to the generally high K status of soils in many of the chicory producing areas internationally. Interaction trials have also been lacking with this element.

In the case of S there has been no definitive work on root chicory per se and thus recommendations rely on S research from other crops. These generally range in a narrow band from 20 to 30 kg S ha⁻¹, and are probably based on estimated crop removal of the element. It is especially sandy soils, where sulphate is lost by leaching, that would warrant attention.

Calcium norms for chicory are non-existent in the literature and very little reliable data on Mg fertilisation levels and norms are given.

As can be seen, quantitative research data are lacking for many of the macronutrients and a concerted effort will be needed to understand the complexities of fertiliser application on different soil types so as to produce meaningful fertiliser norms for root chicory. It is realised

that calibration research is both costly and time consuming, and that therefore careful site selection and planning are required.

The literature is almost devoid of research work on micronutrients for chicory cultivation. Considering that chicory is chiefly grown on soils with a low clay percentage and, in many places on soils that are inherently low in nutrients (Sillanpää, 1990; Karlen et al., 1997; Fageria and Baligar, 2008; Maqubela et al., 2009), further studies are warranted.

Research on soil acidity aspects of root chicory production is patchy and the tolerance level of chicory to acidity is thought to be quite wide. A pH(H₂O) of 4.3 and an acid saturation of 41% have been considered in New South Wales, Australia (Upjohn and Michalk, 1999) as the levels at which forage chicory yield is detrimentally affected. The upper pH limit has not been determined. Chicory, however, is deemed relatively tolerant to alkalinity, as many of the reported research findings have been on neutral to alkaline soils, and it is reported to act as a “nutrient mop” where excess soil nutrients are a problem (Neel et al., 2002). Work is required to determine root chicory’s acid tolerance level so that it can be quantified and the response of chicory to lime needs further study in combination with a range of fertiliser options.

It is apparent that, despite chicory having been grown for many years in many countries, there are still many gaps in knowledge. Work has focused on the more ‘fashionable’ aspects of chicory production, namely forage chicory, inulin production and witloof chicory. The soil fertility requirements for root chicory growth have been neglected. Fertilisation of root chicory for coffee blending purposes has mainly been focused in India, while the move to inulin production has seen the European countries of France, Belgium and the Netherlands focus more on the complexities of its behaviour in the plant to improve output.

Many of the research projects do not state the initial soil fertility levels where experiments were conducted or the full analytical methods used (e.g. phosphate). Usually no mention is made of what the quantitative bases were for the fertilisation rates that were chosen. Most of the research work has focused on the role of N response. Although this is clearly a vital element, the role of the other macroelements and their interactions are poorly known.

With the utilisation efficiencies of fertilisers being questioned, along with concern that fertilisers are non-point sources of pollution in the environment, a concerted effort has to be

made to quantify the fertiliser use of root chicory more fully, given its economic value to producing countries. It is in this light that this project was developed.

CHAPTER THREE

NITROGEN, PHOSPHORUS AND LIME FERTILISATION OF ROOT CHICORY (*Cichorium intybus* var. *sativum*)

3.1 Introduction

Crop production in developing nations is hampered by nutrient deficiencies which impede the attainment of higher yields. Soils of developed nations, in contrast, are usually well supplied with nutrients with some lands even being oversupplied causing imbalances and environmental pollution. Nitrogen (N), phosphorus (P), calcium (Ca) and magnesium (Mg) are some of the most important nutrients for planted crops.

The availability of N sources in the soil varies substantially in time and space, depending on soil properties (Robinson, 1994). It has been suggested by von Wiren et al. (2000) and Forde (2002) that plants have a response function that has been developed over time to regulate N usage depending on the availability of N and the plant's specific N requirements. From research carried out in cooler climates chicory's response to applied N has not been pronounced due to the inherent high availability of soil N, in contrast to warmer environments with lower soil N. By increasing the supply of N, growth is enhanced and this, in turn, increases the demand for other nutrients.

Phosphorus is noted for enhancing the root growth of plants. Silva and Uchida (2000) found that root growth was reduced by P deficiency, despite shoot growth being hampered more than root growth. This was reflected in a lower root mass and is clearly an important consideration for a crop, such as chicory, for which root yield is critical.

Chicory has been reported to thrive in Ca-rich soils (Gill et al., 1980) and it is known that Ca can be supplied at high concentrations, without toxicity or serious impairment of plant growth (Hawkesford et al., 2012). Calcium is a constituent of cell walls and is involved in production of new growing points and root tips. White and Broadley (2003) have reviewed the functions of Ca and have provided a succinct summary of recent developments of Ca as a secondary messenger in plant physiology and molecular biology, linking environmental and developmental stimuli to plant physiological responses.

Magnesium deficiency caused by competing cations is a well-known phenomenon (Kurvits and Kirkby, 1980; Heenan and Campbell, 1981) and in a soil that is low in clay with a

medium to coarse sandy texture, deficiency symptoms can be expected as Mg is a mobile element (Silva and Uchida, 2000). How low soil Mg is expressed in root chicory and if this affects yield to any significant degree have not been fully established. Generally, high Mg concentrations improve the nutritional quality of plants (Grunes et al., 1970; Moseley and Baker, 1991). It has been recognised that Mg is a constituent of the chlorophyll molecule and is essential for the metabolism of carbohydrates (sugars). It is an enzyme activator in the synthesis of nucleic acids and regulates uptake of the other essential elements, serves as a carrier of P compounds throughout the plant, facilitates the translocation of carbohydrates (sugars and starches), and enhances the production of oils and fats (Silva and Uchida, 2000).

The importance of supplying essential nutrients in a balanced manner to the plant is very important for higher yields. In many research papers attention is usually given to a study of one nutrient only (Sumner and Farina, 1986). However, crops are affected by nutrient interactions and yield is affected either positively (synergistic) or negatively (antagonistic). Interactions are complex and often not well understood. Many such interaction trials were conducted internationally in the past as pot experiments under controlled conditions (Sumner and Farina, 1986) and although more interaction work has now been carried out on various crops, field experimentation remains less common due to time and economic constraints. Such field experimentation designed to measure the effects of interaction provide invaluable data regarding attainable yield maxima. The interaction of different nutrients provides the opportunity to improve yield and profitability from an agronomic standpoint and provides an understanding of the importance of a balanced supply of nutrients.

To evaluate root chicory's response to the individual elements and in combination, a three-way nutrient interaction trial was done to determine the optimum values of N, P and lime on a medium sandy loam soil under sprinkler irrigation management. The hypothesis was formulated that root chicory yield would respond significantly to N, P and lime at the 95% level of significance.

3.2 Materials and methods

3.2.1 Site

The study area is located in north-western KwaZulu-Natal Province (KZN), South Africa. The field trial site was located on the Dundee Agricultural Research Station (DARS; 28.137333° S; 30.312000° E), approximately 10 km north east of Dundee (Figure 3.1).

The trial site is 1 215 m above mean sea level (m.a.s.l.) and the trial fields have a 3% slope and face northwest.

Prior to planting root chicory, the site was planted for approximately 20 years to *Eragrostis curvula* (for hay) that was fertilised with 1:0:1(48) at 300 kg ha⁻¹ (N 24%, P 0%, K 24%) and 200 kg ha⁻¹ of superphosphate (10.5% P) year⁻¹.

3.2.1.1 Climate

The climate capability rating of the site is C5 (Natural Resources Working Group, 2013) which is described as having a moderately restricted growing season due to low temperatures, frost and/or moisture stress. The majority (81%) of the mean 743 mm rainfall occurs between October and March as convectional showers. Suitable crops may be grown at risk of some yield loss (Natural Resources Working Group, 2013). Climatic data were sourced from the Agricultural Research Council (ARC) (Agricultural Research Council, 2016) weather station, based at the DARS. Details of the long-term climate record (1968-2012) for the DARS are given in Appendix 3.1. Figures 3.2 and 3.3 illustrate the rainfall and mean temperature conditions, respectively, over the duration of the trial. Rainfall was significantly higher in December in two of the three growing seasons peaking before the long-term mean that occurs in January. The mean temperature during the period April to September was generally higher than the long-term mean.

3.2.1.2 Geology

In general terms the DARS is underlain by rocks of the Karoo Sequence, Ecca Group, Vryheid Formation which consists of sandstone, grey micaceous shales, interleaved by coal seams; intrusive dolerite dykes and sills are also found (Department of Mineral and Energy Affairs, 1988). The trial site itself is underlain by medium to coarse-grained sandstone.

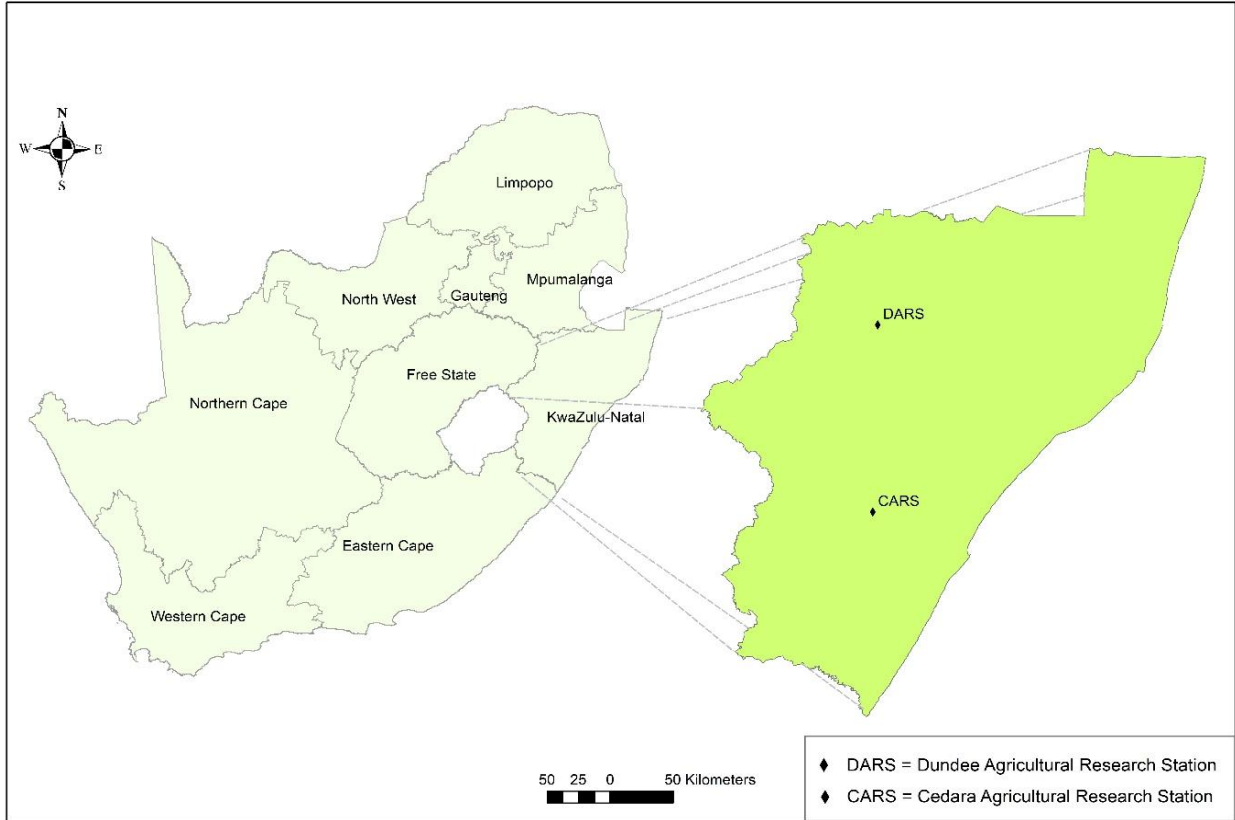


Figure 3.1: Chicory research locations in KwaZulu-Natal Province, South Africa.

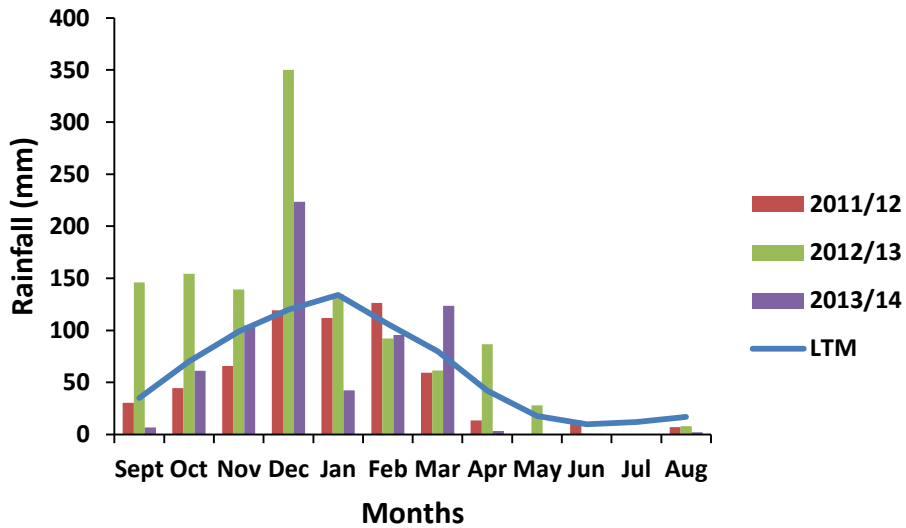


Figure 3.2: Mean monthly rainfall for the trial duration at the Dundee Agricultural Research Station and the long-term (1968-2012) mean (LTM) (Agricultural Research Council, 2016).

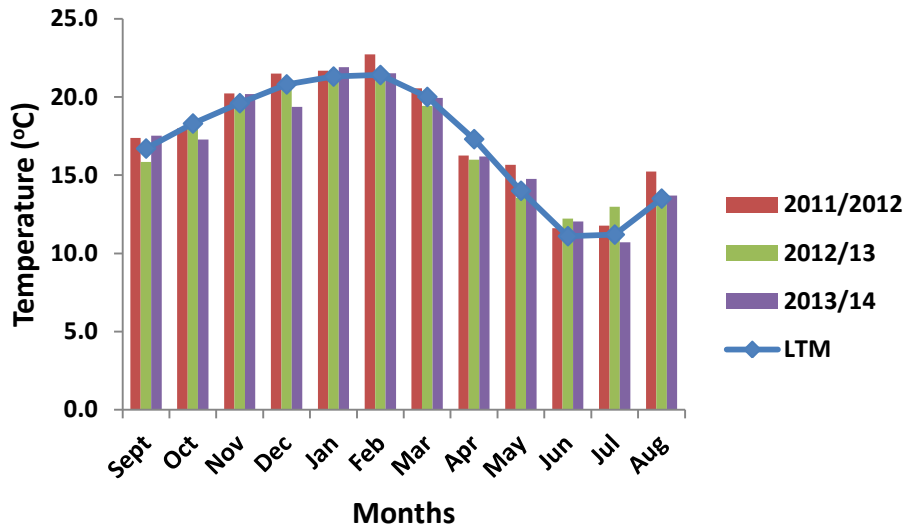


Figure 3.3: Mean monthly temperatures for the trial duration at the Dundee Agricultural Research Station and the long-term (1968-2012) mean (LTM) (Agricultural Research Council, 2016).

3.2.1.3 Soils

The soils at the trial site are plinthic and luvisc in character mainly of the Avalon soil form, Woodburn (1200) soil family (Soil Classification Working Group, 1991, Appendix 3.2); Typic Plinthaquult (Soil Survey Staff, 2014). The chemical and physical properties of the soil at the trial site prior to experimentation are given in Table 3.1. The trial site was chosen as it was considered to represent a soil of moderate potential for root chicory and would thus reflect average yields for the surrounding farming area, representing approximately 550 000 ha determined from Bioresource units of KZN (Natural Resources Working Group, 2013).

Table 3.1: Mean (n=2) selected initial (prior to cultivation) chemical and physical properties of the soil (0-15 cm depth) from the field trial site

Chemical analysis	
Sample density (g mL ⁻¹)	1.33
pH(KCl)	3.86
Acid saturation (%)	43
Exchangeable acidity (cmol _c L ⁻¹)	1.13
Total cations (cmol _c L ⁻¹)	2.64
Phosphorus (mg L ⁻¹)	24
Potassium (mg L ⁻¹)	123
Calcium (mg L ⁻¹)	160
Magnesium (mg L ⁻¹)	48
Organic carbon (%)	1.81
Nitrogen (%)	0.09

Table 3.1 (contd.): Mean (n=2) selected initial (prior to cultivation) chemical and physical properties of the soil (0-15 cm depth) from the field trial site

Textural analysis	
Clay (<0.002 mm)	9.5
Fine silt (0.02-0.002 mm)	7.2
Coarse silt (0.05-0.02 mm)	2.9
Very fine sand (0.1-0.05 mm)	14.1
Fine sand (0.25-0.1 mm)	22.6
Medium sand (0.5-0.25 mm)	26.4
Coarse sand (2.0-0.5 mm)	17.4
Textural class	Loamy sand
Clay mineralogy	Kaolinite with sub-dominant illite

The soil is acidic with low clay and a predominance of medium to fine sand, limited total cations and a low Ca, Mg and N status. Leaching is common on this soil type and applied K, boron and N are particularly affected by this phenomenon. This soil would normally require liming to bring acidity levels down and to increase Ca and Mg levels according to recommendations as outlined by Manson et al. (2012).

3.2.2 Trial design

A confounded factorial design, with two replications (128 plots in total), four rates of N application (0, 80, 160, and 240 kg ha⁻¹ using limestone ammonium nitrate (LAN (28% N) as the N source), four rates of P application (0, 40, 80, and 120 kg ha⁻¹ using single superphosphate (10.5% P) as the P source, which also provided sulphur (S) (13% S) and four rates of dolomitic lime application (0, 2, 4, and 8 t ha⁻¹) were used. The LAN contributed 0, 205, 410 and 615 kg lime ha⁻¹, respectively. The nomenclature used to describe the fertiliser application will subsequently be referred to as N0, N80, N160 and N240 for nitrogen; P0, P40, P80 and P120 for phosphorus; L0, L2, L4 and L8 for lime.

A gross plot size of 4 x 5 m, with a nett plot size of 3 x 4 m, planted to a row spacing of 50 cm, with an inter-plant spacing of 8 cm was used. The number of plants aimed for per gross plot was 525, with 250 per harvested nett plot. The trial (Plate 3.1) comprised 128 experimental plots planted on the 23rd October and harvested on 5th June (220 days) for each of the three growing seasons.



Plate 3.1: Nitrogen x phosphorus x lime trial prior to harvest (11 May 2012).

Dolomitic lime was applied by hand 8 weeks prior to planting according to the plot design. This lime type was chosen due to the inherent shortage of Mg in the loamy sand soil. Boron (B) was applied at a rate of 1.5 kg B ha^{-1} as a spray prior to planting and incorporated during seedbed preparation. Nitrogen was broadcast at planting as it was felt that this deep rooted, biennial crop had the ability to search for nutrients over the 220 day growing period.

The fertilisers were spread by hand prior to planting according to the treatments from the trial design. The fertilisers were incorporated with a Kongskilde Vibroflex® (Kongskilde SA (Pty) Ltd) multi-tine cultivator.

3.2.2.1 Land preparation and planting

The land was disced twice with a heavy offset tandem cultivator (G.C. Tillage Company (Pty) Ltd Model 22/55®). This was followed by two passes with a Kongskilde Vibroflex® (Kongskilde SA (Pty) Ltd) multi-tine cultivator to create a fine seed-bed. A roller was used twice prior to planting to produce a firmer base for planting.

During the 2011-2012 season planting depth was set at 10-15 mm. This resulted in a lower plant population of 127 plants per nett plot at a row spacing of 50 cm. In the following two

growing seasons the planting depth was altered to 2-5 mm with the same row spacing as in the 2011-2012 season. A vegetable hand planter (Earthway Precision Garden Seeder® Model 1001-B) was used, using a carrot planting plate, with every second hole blocked for planting. An inter-plant spacing of 8 cm was achieved at 35-40 days after sowing (DAS) by thinning.

3.2.2.2 Weed, nematode control and irrigation

Balan® (active ingredient (a.i.)-benfen), the only product registered in South Africa for chicory, was used as a pre-emergence herbicide for the control of grass and some broadleaf weeds. At 46 DAS, a knapsack sprayer with shields, containing Gramoxone® (a.i. paraquat) was used to spray between the rows. At 65 DAS hand hoeing was done to remove any persistent weeds. Once the crop had a complete canopy further weed control was unnecessary. A nematicide (Rugby®) (a.i. Cadusafos) was sprayed according to specifications prior to planting chicory and at 75 DAS.

During the initial germination period, frequent light irrigations (3 mm, three times a day) were applied by overhead sprinkler irrigation to cool the soil, as soil temperatures increased above 24°C in the top 100 mm, which according to the RTFA (2010, 2015) is the critical upper limit for chicory germination. Irrigation was subsequently applied on a supplementary basis with 30 mm being added weekly if no rain had fallen. Water of good quality (Appendix 3.3) was supplied from a nearby dam.

3.2.3 Experimental procedure

3.2.3.1 Soil sampling and analysis

Prior to cultivation representative A-, B- and C-horizon samples were taken from across the trial site. The A-horizon samples were taken with a Beater auger and the B- and C-horizon samples with a Dutch soil auger. In total 25 auger points were sampled per plot. The samples were then bulked and mixed per horizon and representative samples taken for seven fraction particle size distribution and soil fertility analysis.

After cultivation each plot's topsoil (0-15 cm) was randomly sampled with a Beater auger to obtain 25 samples per plot which were mixed thoroughly to obtain a bulked representative sample. In addition, topsoil and subsoil samples were taken after each harvest for fertility analysis. The subsoils were sampled by hand auger from 30-45 and 45-75 cm. Fifteen

samples were collected and bulked per plot, and a representative sample taken. The soil samples were sent to the soil laboratory at the Cedara Agricultural Research Station (CARS) for analysis of sample density, P, potassium (K), Ca, Mg, exchangeable acidity, total cations, acid saturation percentage, pH(KCl), extractable zinc (Zn), manganese (Mn) and copper (Cu), clay, organic carbon, nitrogen (N), and carbon : nitrogen ratio using procedures described by Hunter (1975) and Farina (1981). The analytical procedure followed for soil analysis is given in Appendix 3.4.

3.2.3.2 Leaf sampling and analysis

Leaf sampling was carried out on all plants twice during the growth of the crop at 60 DAS and prior to harvest at 220 DAS. Use was made of the procedure as adapted from Reuter and Robinson (1997) whereby the youngest fully open leaf was harvested. The leaf samples (25 leaves per plot) were sent to the plant laboratory at the CARS for analysis of N, Ca, Mg, P. The analytical procedure followed for leaf analysis is given in Appendix 3.5.

3.2.3.3 Root sampling and analysis

From the 2014/2015 harvest a random sample of 10 visually healthy roots per plot were selected, washed, weighed and sliced into 5 mm cross sections and force air dried at 65°C in an oven (Unitherm Drier®). After drying the samples were weighed and then sent to the plant laboratory at the CARS for analysis of the same plant tissue elements as described in Section 3.2.3.2.

3.2.3.4 Harvest

At harvest the nett plot roots (approximately 250 per plot) were weighed using a portable suspended electronic scale (Scaletec model SHS 50®). The wet weight of the roots and number of healthy and diseased roots were recorded. A random sample of 20 roots per plot was taken and dried to determine the dry weight. The weight of the leaves in the nett plot was determined with the same suspended electronic scale and a grab sample taken per plot for moisture determination. Root length was measured with a steel tape and width determined with an electronic vernier (Lutron DC515 ®) 2 cm from the top of the root. All leaf material after harvest was finely chopped with a garden shredder (Bosch AXT25TC®) and then returned to the respective plot and incorporated by hand.

3.2.3.5 Statistical analysis

The results were subjected to analysis of variance (ANOVA) using GenStat® version 18.1 software (VSNi, 2015). Combined ANOVAs of multiple harvests were carried out using repeated measures analysis after testing the homogeneity of error mean squares from the individual ANOVA (Gomez and Gomez, 1984). Fisher's test of least significant difference (l.s.d.) was conducted at a 5% significance level.

3.3 Results and discussion

3.3.1 Nitrogen

3.3.1.1 Yield

As discussed in Section 3.2.2.1 the first season of planting had a lower plant population and resulted in a significantly lower yield as compared to the latter two seasons. The highest yield was obtained at 240 kg N ha⁻¹ (Figure 3.4) but the best root quality was obtained with 160 kg N ha⁻¹. Root quality was determined by randomly selecting 25 roots per plot and visually categorising the roots into two classes namely with and without disease and allocating a percentage to the overall treatment. The following discussion refers to the mean yields over all three seasons (2011-2012; 2012-2013; 2013-2014).

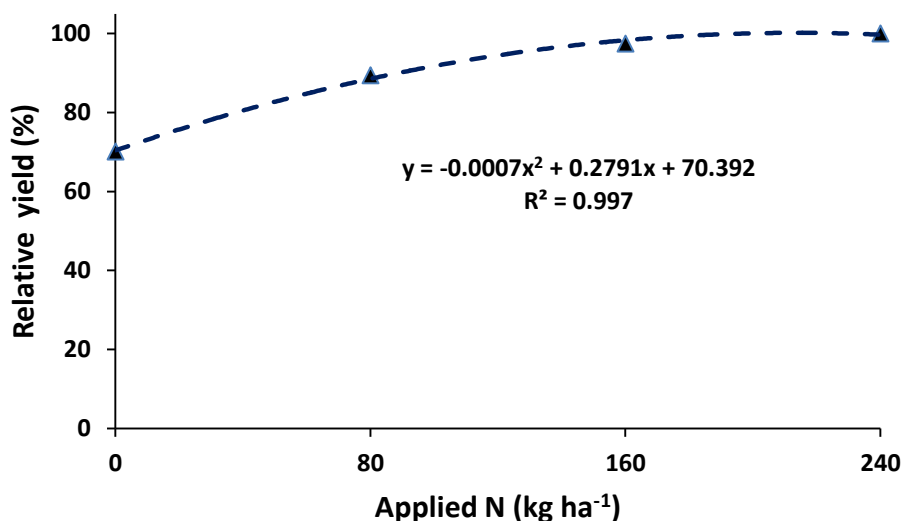


Figure 3.4: Mean (n=6) relative yield of root chicory with different amounts of applied nitrogen (N) over all three seasons (CV% 13.2, l.s.d. 3.217, S.E.M. 4.846 at p<0.05).

Yields tended to show a good response to 80 kg N ha⁻¹ with an 89.41% relative yield. In fertiliser experiments, 90% of the maximum yield is considered as an economic index (Fageria et al., 2010) and can be regarded as an economic optimum for growers. The differences in yield and their significance are given in Table 3.2 and Appendix 3.6. With the addition of 160 kg N ha⁻¹ a 23% increase in wet yield was achieved. However, a large proportion of this increase (13%) was achieved with the application of 80 kg N ha⁻¹. Root length was not significantly increased by the addition of N. However, herbage yield (Table 3.2) and root width (Table 3.3) were significantly increased with the addition of 240 kg ha⁻¹. Although as the N application rate increased the leaf : root dry weight ratio and the harvest index (Hay, 1995) (root mass / total biomass) did not change significantly (Table 3.2). Related to this, the N utilisation efficiency (total dry yield / applied N, as defined by Bock, 1984) was lower. At the highest N application rate (240 kg N ha⁻¹) root quality deteriorated significantly (p<0.05) with the number of diseased roots increasing to 15% (Table 3.2), although yields were slightly higher than at N160.

Table 3.2: Mean (n=6) root and leaf yields, leaf : root ratio, harvest index (root mass / total biomass), nitrogen utilisation efficiency and diseased roots with different amounts of applied nitrogen (N) over all three seasons

Applied N (kg ha ⁻¹)	Root yield (wet) (t ha ⁻¹)	Root yield (dry basis) (t ha ⁻¹)	Leaf yield (dry basis) (t ha ⁻¹)	Leaf : root (dry basis)	Harvest index	N utilisation efficiency (kg DM* kg ⁻¹ N)	Diseased roots (%)
N0	31.76 ^{a#}	8.25	4.05 ^a	0.49	0.67	–	0
N80	35.90 ^b	9.08	4.43 ^b	0.49	0.67	169	1
N160	39.12 ^c	9.89	4.68 ^c	0.50	0.67	88	3
N240	40.15 ^c	10.14	5.22 ^d	0.52	0.66	64	15

* DM – dry matter

- values with different superscripts within a column are significant. Root yield (wet): CV% 13.2, l.s.d. 3.217, S.E.M. 4.846; Leaf yield: CV% 2.5, l.s.d. 0.15163, S.E.M. 0.11570 all at p<0.05.

Table 3.3: Mean root length and root width (n=6) with different amounts of applied nitrogen (N) for each of the three seasons

Applied N (kg ha ⁻¹)	Root length (cm)				Root width (cm)			
	2012	2013	2014	Mean	2012	2013	2014	Mean
N0	24.7	25.6	26.0	25.5 ^{a#}	3.5	3.6	3.7	3.6 ^a
N80	24.6	25.8	26.0	25.5 ^a	3.7	3.9	4.0	3.8 ^b
N160	25.5	26.1	26.7	26.1 ^a	3.7	3.8	4.1	3.9 ^b
N240	25.5	26.7	27.1	26.4 ^a	4.0	4.1	4.3	4.1 ^c

- values with different superscripts within a column are significant ($p < 0.05$). Root length: CV% 3.3, l.s.d. 0.6831, S.E.M. 0.8532. ; Root width: CV% 6.0, l.s.d. 0.2155, S.E.M. 0.2308 all at $p < 0.05$.

In India, Patel (1958) reported 11.2 and 7.9% increases in fresh and dry root yields, respectively, following application of 40 lb N acre⁻¹ (45 kg N ha⁻¹) and these probably would have been greater if additional N had been applied. Doida (1977), at Anand, India under irrigation, observed increases in growth and yield of fresh and dry roots, herbage, root length and volume of root chicory with an increase in applied N from 50 to 125 kg N ha⁻¹.

Patel et al. (2000) also did research on a sandy loam soil, low in total N but in contrast with the DARS soil (that had a pH(KCl) of below 4.0) their soil had a pH(H₂O) of 7.9. Their findings indicated that fresh and dried root yields were improved markedly with up to 100 kg N ha⁻¹ applied in two of the three seasons. Khaghani et al. (2012), Moosavi (2012) and Seghatoleslami et al. (2014), all in Iran, found a positive increase in yield of root chicory using 69, 180 and 200 kg N ha⁻¹, respectively, on variously textured soils. The lower clay soils showed a higher N requirement. Patel et al. (2000) in India also reported low residual N of 0.032-0.034% N, similar to the present trial.

MAFF (1988) indicated that for soils that have low N, 150 kg ha⁻¹ should be applied, while other soils, excluding fen peats (organic soils), should receive 75 kg ha⁻¹. The DARS trial site can be regarded as falling in the former category of soils.

In terms of the interactions of nutrients there was a greater yield response to N at high levels of P (29% at P120 compared to 18% at P0) (Table 3.4). A number of possible mechanisms can be proposed to account for this interaction. These include an increase in N absorption as a result of P increasing root growth (Wilkinson et al., 1999) which increases the ability of roots

to absorb and translocate P, and a decrease in soil pH as a result of absorption of NH_4^+ thereby increasing the solubility of fertiliser P (Wilkinson et al., 1999).

Table 3.4: Interaction of applied nitrogen (N) and phosphorus (P) on the mean (n=6) wet yield (t ha^{-1}) of root chicory across all three seasons

Treatment (kg ha^{-1})	P0	P40	P80	P120
N0	31.62 ^{a#}	32.00 ^a	30.24 ^a	33.19 ^a
N80	34.38 ^a	38.04 ^b	37.54 ^b	33.64 ^a
N160	35.90 ^a	36.20 ^b	41.44 ^b	42.92 ^b
N240	37.24 ^a	40.46 ^b	39.94 ^b	42.97 ^b

- values with different superscripts within a column are significant. CV% 13.2, l.s.d. 4.677, S.E.M. 4.846 at $p < 0.05$.

3.3.1.2 Soil nitrogen

In this study N was not based on soil analysis, as it is considered unreliable because of the speed of N reactions in the soil (Manson, 1994). The processes of mineralisation, leaching and denitrification can change the quantities of available mineral N in a short period of time. However, mid-infrared analysis (MIR) was used to give an indication of total organic soil N. Low MIR-N is common at the trial site with 0.040% a typical value. It was established that the interaction between applied N, P and lime had a moderately significant ($p=0.054$) effect on MIR-N (Appendix 3.7). This may be related to soil changes as a result of the application of lime. This plays an important role in the plant-availability of elements but there are confounding issues especially with the lime x P interaction (Haynes, 1982). For acid soil, (as at the trial site), the main issue concerns air-drying. Without air-drying, liming can increase P adsorption (as in the field trial) whereas if the same soil is air dried before reaction with P it has been found that liming decreases P adsorption. It seems as if the air-drying changes the external characteristics of soils that have recently been limed, and it is suggested that this promotes the crystallisation of hydroxyl-Al cation polymers such as gibbsite (Haynes, 1982). Magnesium, Ca and silicon (Si) ions are noted for their interaction with P, in addition to other elements affected by pH changes (Adams, 1980). Kawasaki (1995) also noted that, for a range of crops, Ca levels in the plant were higher in the presence of $\text{NO}_3\text{-N}$ as the N source in nutrient solution compared to $\text{NH}_4\text{-N}$. This might be related to the inhibiting effect of $\text{NH}_4\text{-N}$

on Ca absorption (Sumner and Farina, 1986). It is thus quite difficult to quantify how the different interactions under field conditions give a definitive result due to other confounding variables.

3.3.1.3 Leaf nitrogen

The first sampling at 60 DAS was during the rapid growth phase of the chicory in which active translocation of nutrients occurs. The second prior to harvest (220 DAS) at the beginning of June represented a time of limited growth. Differences in N were evident between the two sampling times and are shown as the mean across the three harvests (Figure 3.5).

The absorption of N in the leaf at the first leaf sampling can be described using a polynomial function with $R^2 = 0.92$. The relative yield percentage showed an initial rapid change in slope up to N160 after which the increase was more gradual to N240, suggesting that 160 kg N ha⁻¹ is the turning point for N under the trial conditions. A mean leaf N concentration of 3.74% at 60 DAS corresponded to an applied rate of 160 kg N ha⁻¹. A concentration range of 1.71 to 4.56% N was found over the three-year period for the 60 DAS sampling. Significantly ($p < 0.05$) lower yields were recorded between 1.71 and 3.30% N at 60 DAS (Appendix 3.8).

The critical level (10% growth reduction) of N in many plants is around 3% (Campbell, 2000) when sampled using the most recently matured leaf (Hochmuth et al., 2009), during a specific growth stage of a plant. When the N in leaves drops below 2.75%, N deficiency symptoms appear and yield (<80% of maximum yield) and quality decline (Reuter and Robinson, 1997). Work done in north-western Croatia by ČustiĆ et al. (2003) showed that for an average crop, head chicory N values were fairly uniform at 2.92-3.69%.

There was a significant interaction between leaf N at 60 DAS and lime ($p = 0.002$) (Appendix 3.8) which can in all likelihood be ascribed to the pH change brought about by lime on the availability of nutrients to the plant.

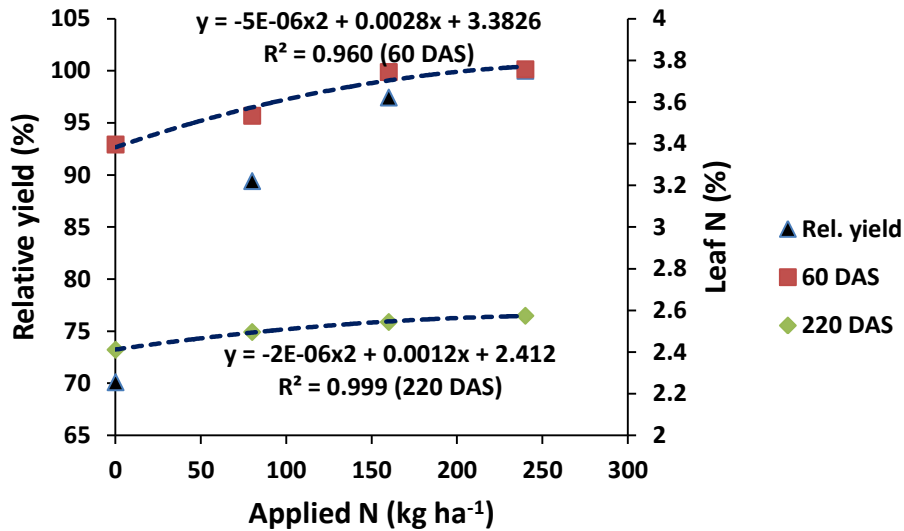


Figure 3.5: Leaf nitrogen (N) at 60 and 220 days after sowing (DAS) and relative yield with different amounts of applied N as a mean over three harvests (n=6) (Leaf N% at (a) 60 DAS: CV% 9.7, l.s.d. 0.1818, S.E.M. 0.3509; and (b) 220 DAS: CV% 8.9, l.s.d. 0.1156, S.E.M. 0.2229 all at p<0.05).

3.3.1.4 Root nitrogen

There was a progressive increase in the mean N% in the root with increasing N treatment (Table 3.5). Values below 0.9% N were associated with poor yields while 0.9 to 1.1% N gave average to good yields. Not much research has been done on root nutrient levels for chicory except for farmers practising chicon production in Holland and Belgium. The RTFA (2010, 2015) referred to work done by Sarrazyn and Deckers (1991) that suggested roots for chicon development at harvest should have a target amount of between 0.7 and 1.3% N, depending on the stage of forcing, to secure adequate production. The results from the present trial support these target values. Marle and Roux (1991) suggested that the N content of the root determines the final quality of the chicory heads. A root dry matter content with N lower than 1% is favourable for head quality. In the N160 and N240 treatments the root N% was slightly higher than this. More than 1.2% N increases the sensitivity of the chicory heads to bacteria and to pith deformations (brown pith), which result in a decrease in quality, as was experienced from the trial with the number of diseased roots (Table 3.2).

Table 3.5: Mean (n=2) root nitrogen (N) with different amounts of applied N for the 2014/2015 season

Applied N (kg ha ⁻¹)	Mean root N (%)
N0	0.93 ^{a#}
N80	0.98 ^{ab}
N160	1.02 ^{bc}
N240	1.06 ^c

- values with different superscripts are significant. CV% 12.3, l.s.d 0.0609, S.E.M. 0.1225 at p<0.05).

Van Nerum (1983), Marle and Roux (1991) and Vandendriessche et al. (1993) stated that total N generally represents only 1% of the root dry weight and the present results concur with this. No significant interactions between root N, P and lime and combinations thereof were evident (Appendix 3.9).

3.3.2 Phosphorus

3.3.2.1 Yield

A non-significant increase in yield was evident (Figure 3.6; Table 3.6) with the application of increasing amounts of P, with relative yields consistently over 90%. This could be because the initial soil P level of 23 mg P L⁻¹ was not low enough to produce a significant response to added P. The P x N interaction with yield was significant (Appendix 3.6). Root length and width were non-significant with the addition of the applied P (Table 3.7) in the pooled analysis. The amount of leaf material was also found to be non-significant, while the leaf : root ratio decreased with increasing P. The harvest index and the percentage of diseased roots did not show significant differences (Table 3.6). The leaf and root yield at the different treatment levels removed between 30.15 and 33.06 kg P ha⁻¹ (Table 3.8). The P80 and P120 treatments applied P well in excess of these levels. The current (2017) cost for P is R10.00 kg⁻¹, which equates to R450 and R850 ha⁻¹, unnecessary expenditure, respectively, although this would depend on the value of the increased yield. The current (2017) value of chicory is R 1 200 ton⁻¹, a 1.60% (P80) and 3.93% (P120) increase in yield above P40, respectively, would not justify the application of the additional amount of phosphate fertiliser.

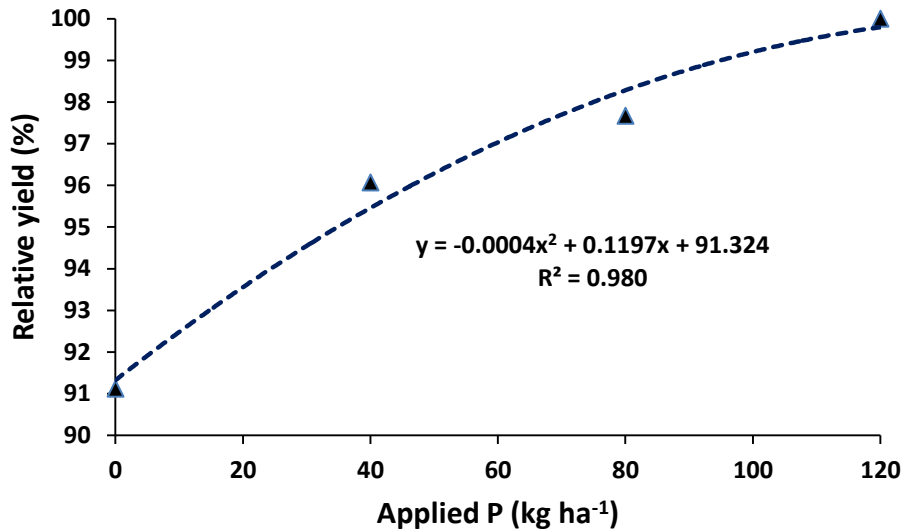


Figure 3.6: Mean (n=6) relative yield of root chicory with different amounts of applied phosphorus (P) (CV% 13.2, l.s.d. 3.217, S.E.M. 4.846 at p<0.05).

Table 3.6: The effect of different amounts of applied phosphorus (P) on mean (n=6) root and leaf yields, leaf : root ratio, harvest index (root mass / total biomass) and percentage of diseased roots

Applied P (kg ha ⁻¹)	Root yield (wet basis) (t ha ⁻¹)	Root yield (dry basis) (t ha ⁻¹)	Leaf yield (dry basis) (t ha ⁻¹)	Leaf : root (dry basis)	Harvest index	Diseased roots (%)
P0	34.79 ^{ns#}	8.49	4.58 ^{ns}	0.539	0.65	1
P40	36.68 ^{ns}	8.95	4.50 ^{ns}	0.503	0.67	1
P80	37.29 ^{ns}	9.34	4.63 ^{ns}	0.496	0.67	0
P120	38.18 ^{ns}	9.31	4.67 ^{ns}	0.502	0.67	0

[#]ns - not significant. Root yield (wet): CV% 13.2, l.s.d. 3.217, S.E.M. 4.846 ; Leaf yield: CV% 2.5, l.s.d. 0.15163, S.E.M. 0.11570 all at p<0.05.

Table 3.7: Mean (n=6) root length and root width with different amounts of applied phosphorus (P)

Applied P (kg ha ⁻¹)	Root length (cm)				Root width (cm)			
	2012	2013	2014	Mean	2012	2013	2014	Mean
P0	24.7	25.6	26.0	25.4 ^{ns#}	3.5	3.6	3.7	3.7 ^{ns}
P40	24.8	25.7	26.3	25.6 ^{ns}	3.6	3.8	3.9	3.8 ^{ns}
P80	25.4	26.2	26.6	26.1 ^{ns}	3.8	3.9	4.0	3.9 ^{ns}
P120	25.5	26.7	27.0	26.4 ^{ns}	3.8	4.0	4.3	4.0 ^{ns}

[#]ns - not significant. Root length: CV% 3.3, l.s.d. 0.6831, S.E.M. 0.8532; Root width: CV% 6.0, l.s.d. 0.2155, S.E.M.0.2308 all at p<0.05.

Table 3.8: Mean (n=6) dry root yield, phosphorus (P) concentrations and P uptake by leaves and roots of root chicory with different amounts of applied P

Applied P (kg ha ⁻¹)	Root P concentration (dry basis) (%)	Root P uptake (kg P ha ⁻¹)	Leaf P concentration (dry basis) (%)	Leaf P uptake (kg ha ⁻¹)	Total P removed (kg P ha ⁻¹)
P0	0.22	18.7	0.25	11.45	30.15
P40	0.22	19.69	0.25	11.25	30.94
P80	0.23	21.48	0.25	11.58	33.06
P120	0.22	20.48	0.25	11.68	32.16

Patel et al. (2000) reported that P failed to exert a significant influence on fresh and dry root and herbage yields of chicory either during the individual years of study or on an integrated basis, except for herbage yield in one of the seasons. However, although their research was done on soils with a similar texture to that at the DARS, they contained much more plant-available P (pre-fertiliser) than the DARS soil i.e., 62.0-81.2 kg ha⁻¹ (P₂O₅) (36-47 mg P L⁻¹).

Orchard and Van Rooyen (1953) used 14 and 28 kg P ha⁻¹, to determine the yield response of root chicory. They found on the low clay soils (<15%) of the Eastern Cape Province that P significantly increased root yield. The full P response was obtained, under dryland conditions, from the lower application rate, and there was no added advantage from application of the

higher rate. However, the initial soil P status was not indicated. In contrast, Greyling (2010) reported that a high P application of between 60 and 80 kg P ha⁻¹ per season was required on a sandy soil, but the research basis for this amount was not given.

From the literature, P response and application rate is divided into two groups i.e., a higher P application to the witloof and leafy chicory and a lower P requirement for forage chicory. However, there has been an apparent change in approach from the earlier research work (1975-1995) in which higher rates of P were more favoured as compared to later research which tends to encompass the recent debate of P pollution in the environment. In support of the debate are the high prices of P, and that P is a finite resource (Withers et al., 2001a,b; Withers et al., 2005; Withers et al., 2014).

3.3.2.2 Soil phosphorus

All the P treatments had a highly significant positive effect on soil P ($p < 0.001$) with relative yield showing a positive trend with increasing soil P but it was not significant at $p > 0.05$ (Appendix 3.7). The steepest incline of the relative yield curve (Figure 3.7) was achieved up to a soil P value of 31 mg P L⁻¹ (P40) at a relative yield of 96%; thereafter the response was less.

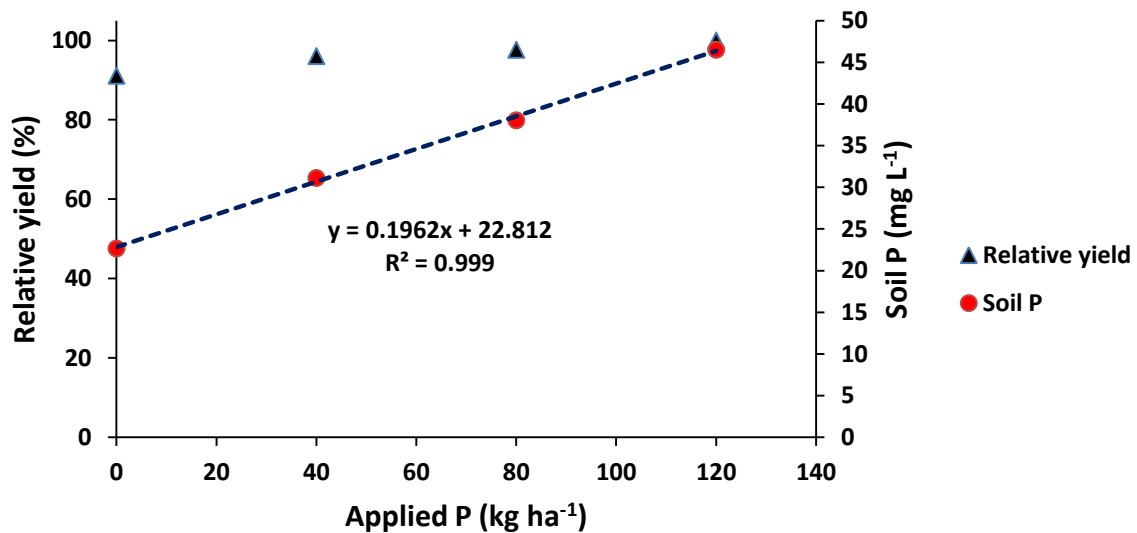


Figure 3.7: Soil phosphorus (P) with different amounts of applied P and corresponding relative yield over three seasons (n=6) (Soil P: CV% 29.4, l.s.d. 6.219, S.E.M. 10.168 at $p < 0.05$).

There was a moderately significant ($p=0.063$) interaction between applied P, N and lime in the soil (Appendix 3.7). There is often a significant positive interaction between the effects of N and P on plant growth (Terman et al., 1977; Sumner and Farina, 1986; Baligar et al., 2001). This increase in growth requires both more N and more P and is synergistic as enhanced growth stimulates uptake of both elements (Sumner and Farina, 1986; Baligar et al., 1990). Similarly, the influence of dolomitic lime is not only on the prevalence of Ca, Mg and often Si (Sumner and Farina, 1986) but it also has a strong influence on pH which, in turn, affects nutrient availability and ultimately growth. Interactions between P and Mg are likely as Mg is an activator of kinase enzymes and is involved in many reactions involving P transfer (Fageria, 2001).

3.3.2.3 Leaf phosphorus

Leaf P at the first leaf sampling (60 DAS) decreased with increasing yield (Figure 3.8). The mean range of leaf P over the three years during this active growth phase varied from 0.42% at low applied P to 0.39% P at P120 (Appendix 3.8). The total range was 0.28 to 0.54% P and values of $>0.40\%$ P were associated with good yields within the trial. Leaf P did not vary significantly with fertilisation treatment. The second leaf sampling (220 DAS) remained almost constant at 0.25% P in a period of slow growth. The plant P requirement is usually highest when it is in its early growth phase and declines with age. The results from the trial seem to correspond fairly well with those of Čustić et al. (2003) working with leafy chicory. They also found that in head chicory leaf % P did not vary significantly with fertilisation treatment with values ranging from 0.38 to 0.55% P in the plant tissue with applied P fertilisation rates of 44 to 131 kg ha⁻¹.

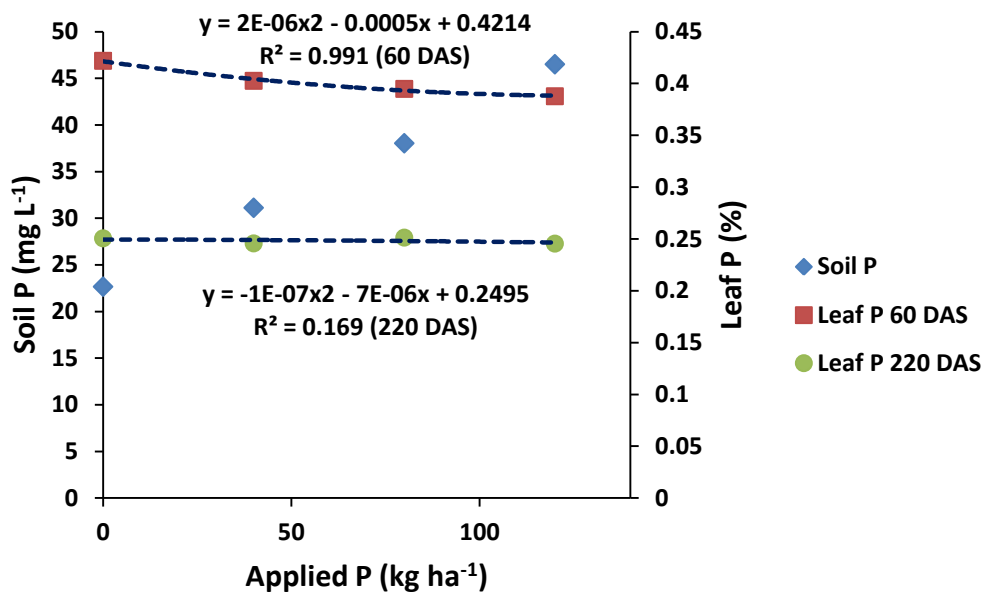


Figure 3.8: Mean (n=6) leaf phosphorus (P) at the first sampling (60 days after sowing (DAS)) and second sampling (220 DAS) and mean (n=6) relative yield with different amounts of applied P (Leaf P% at (a) 60 DAS: CV% 13.3, l.s.d. 0.02470, S.E.M. 0.05334; and (b) 220 DAS: CV% 11.3, l.s.d. 0.01444, S.E.M. 0.02806 at p<0.05).

There was a highly significant ($p < .001$) relationship between leaf P and applied N and P, while applied lime was significant at $p < 0.05$. Interactions between leaf P, and applied N x P (Figure 3.9), and N x lime were significant and moderately significant, respectively (Appendix 3.8). The interaction of P with N is regarded as probably one of the most important reactions involving P (Sumner and Farina, 1986). Increasing soil P above 31 mg P L⁻¹ resulted in a rapid decline in leaf P in the presence of increasing N application, and could be due to the dilution effect (Jarrell and Beverly, 1981) as N application has been shown to significantly increase chicory yield or it could possibly be the result of yield limits or levels of sufficiency being approached (Sumner and Farina, 1986).

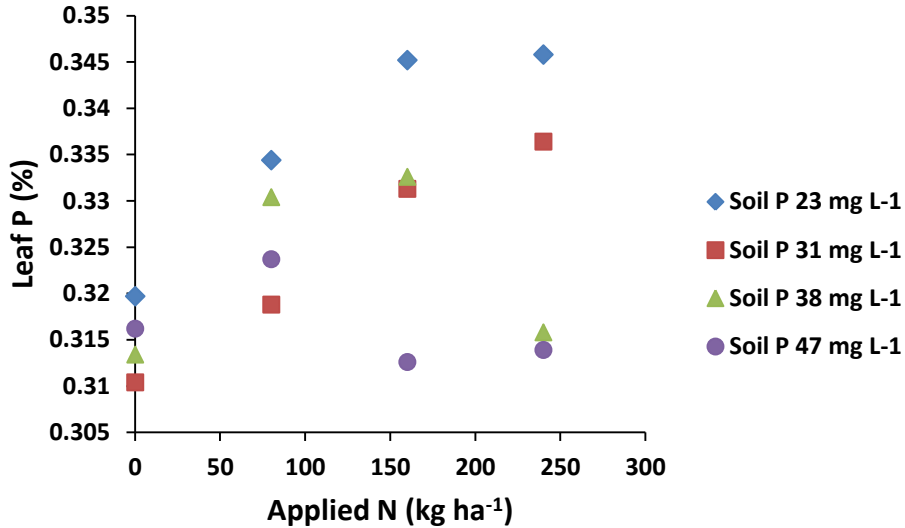


Figure 3.9: Interaction of mean (n=6) leaf phosphorus (P) at 60 and 220 days after sowing (DAS) at different soil P levels with different amounts of applied nitrogen (N) over three seasons (Leaf P% at (a) 60 DAS: CV% 13.3, l.s.d. 0.04941, S.E.M. 0.05334 and (b) 220 DAS: CV% 11.3, l.s.d. 0.01444, S.E.M. 0.02806 all at $p < 0.05$).

3.3.2.4 Root phosphorus

A moderate interaction ($p=0.027$) occurred between applied P and root P (Figure 3.10) which ranged from 0.21 to 0.23% P. The highest yield was attained with root P of 0.22% P. The RTFA (2010, 2015) cited work done by Sarrazyn and Deckers, (1991) that suggested roots at harvest should have a target amount of 0.23 to 0.28% P for forcing to secure adequate chicon production. The current trial results would just make this target minimum at the highest yield achieved. Phosphorus levels in the root were also significantly associated with the lime applied ($p=0.005$) (Appendix 3.9). However, there was no evidence of interactions between nutrients at this sampling stage. Possibly, if the root were sampled during an active growth stage an interaction could have resulted due to translocation of certain nutrients. Liming inevitably affected soil pH (Section 3.3.3.2) which could have had an impact on P availability to the plant, but this depends on the crop and the soil conditions. In earlier years (1940's and 1950's) the paradigm at that time suggested that P was more available near neutral soil conditions (soil pH 6.5-7.5) and declined at lower and higher pH (Truog, 1946). However, there are conflicting research reports on P availability and lime (e.g. Foy et al., 1978; Adams, 1980; Haynes, 1982; Sumner and Farina, 1986) and this earlier view was altered resulting in a paradigm shift as interactions of P with pH in the moderately to slightly acidic range (pH 5.5 to 6.5) were found to be more complex. A host of tests (laboratory, field and glasshouse) have

suggested that increases in pH within this range may increase, decrease, or have no effect on P availability to plants (Haynes, 1982).

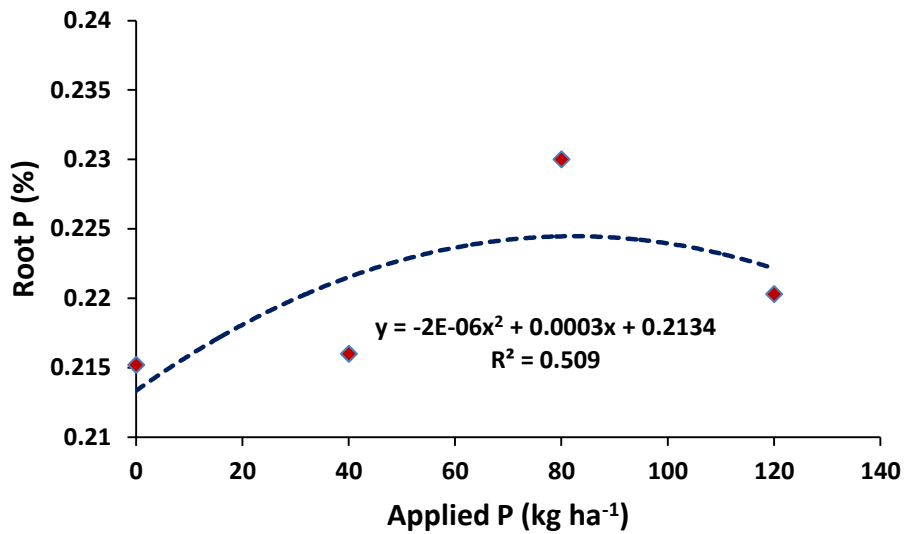


Figure 3.10: Mean (n=2) root phosphorus (P) with different amounts of applied P for the 2014/2015 harvest (CV% 9.8, l.s.d. 0.01070, S.E.M. 0.02152 at p<0.05).

3.3.3 Lime

3.3.3.1 Yield

Lime increased yields in both the integrated and individual harvests (Appendix 3.6) up to the maximum applied of 8 t ha⁻¹ (Figure 3.11 and Table 3.9). This was expected as the initial soil pH(KCl) was below 4.0. The greatest increase occurred from L0 to L2 which could have been not only due to a change in soil pH but also as a response to the initial low soil Ca of 160 mg Ca L⁻¹ prior to the start of the trial (pre-cultivation) (Table 3.1). pH has a large influence on plant growth due to its effect on the availability of nutrients (Foth, 2003). However, at the pH of this soil the benefits of lime probably include the reduction or prevention of toxicity caused by free Al and Mn in the soil solution (Weil and Brady, 2016).

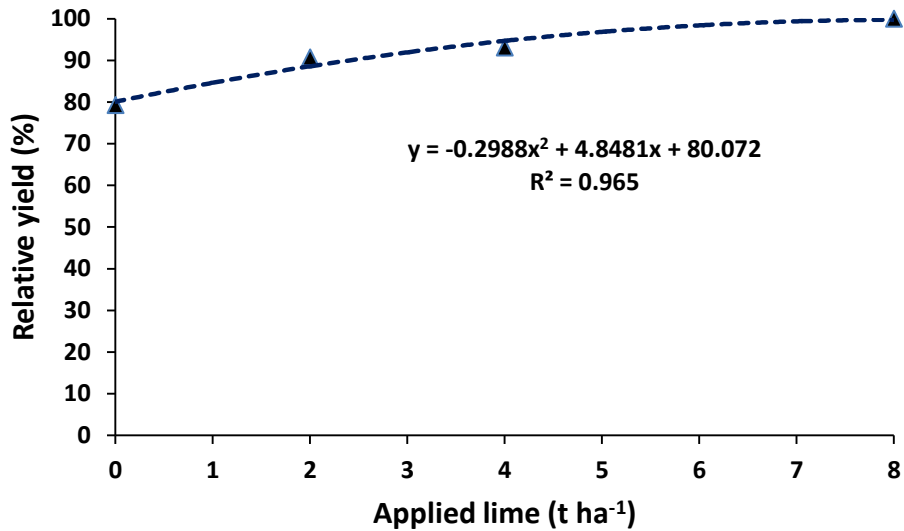


Figure 3.11: Mean (n=6) relative wet yield of root chicory with different amounts of applied dolomitic lime (CV% 13.2, l.s.d. 3.217, S.E.M. 4.846 at p<0.05).

The continuing positive response to lime in the field experiment at the highest rate applied suggests that chicory is tolerant of soils with higher pH, as has been reported by other researchers who worked on neutral to alkaline soils (Patel et al., 1990; Patel et al., 2000; Boyd and Rogers, 2004).

Root length and width was significant in the pooled analysis (Table 3.10). Leaf yields showed a significant difference between treatments probably as a result of the positive reaction to calcium. The leaf : root ratio and harvest index were only significant between L0 and L2 while the percentage of diseased roots was not significant (Table 3.9).

Table 3.9: Effect of applied lime (L) on root and leaf yields, leaf : root ratio, harvest index (root mass / total biomass) and percentage of diseased roots as a mean (n=6) over three seasons

Applied lime (t ha ⁻¹)	Root yield (wet basis) (t ha ⁻¹)	Root yield (dry basis) (t ha ⁻¹)	Leaf yield (dry basis) (t ha ⁻¹)	Leaf : root (dry basis)	Harvest index	Diseased roots (%)
L0	32.08 ^{a#}	8.27	4.30 ^a	0.390	0.72	2
L2	36.71 ^b	9.41	4.48 ^b	0.456	0.69	1
L4	37.67 ^b	9.93	4.70 ^c	0.451	0.69	0
L8	40.47 ^b	10.38	4.90 ^d	0.452	0.69	0

- values with different superscripts within a column are significant. Root yield (wet): CV% 13.2, l.s.d. 3.217, S.E.M. 4.846 ; Leaf yield: CV% 2.5, l.s.d. 0.15163, S.E.M. 0.11570 all at p<0.05.

Table 3.10: Mean (n= 6) root length and root width with different amounts of applied lime (L) each season

Applied lime (t ha ⁻¹)	Root length (cm)				Root width (cm)			
	2012	2013	2014	Mean	2012	2013	2014	Mean
L0	23.544	22.969	23.534	23.349 ^{a#}	2.775	2.794	2.844	2.804 ^a
L2	24.531	25.069	25.150	24.917 ^b	3.459	3.572	3.687	3.573 ^b
L4	25.812	26.750	27.191	26.584 ^c	4.016	4.125	4.219	4.120 ^c
L8	26.281	29.444	30.034	28.586 ^d	4.578	4.887	5.225	4.897 ^d

- values with different superscripts within column are significant. Root length: CV% 3.3, l.s.d. 0.6831, S.E.M.0.8532; Root width: CV% 6.0, l.s.d. 0.2155, S.E.M. 0.2308 all at p<0.05.

3.3.3.2 Soil calcium, magnesium, pH and acid saturation

Lime played a prominent role in altering Ca and Mg levels in the soil. In addition, it had a significant effect on acid saturation, pH, and extractable Zn and Mn in the soils sampled due to the effect of increasing soil pH (Chapter 6). The mean soil pH(KCl) 8 months after lime application ranged from 4.08 at L0 to 4.69 at L8. After completion of the trial (Table 3.11) a further increase in pH(KCl) was observed from 4.47 (L0) to 5.44(L8). The change in soil pH was significant between L2 and L4 a result of the buffering capacity of this soil being surpassed. The difference between L4 and L8 pH results can be explained as proportionally more lime is required to attain very low levels of acid saturation in the soil. This results from

a stronger buffering capacity at the lower acid saturation levels (Manson et al., 2012). The change in pH and acid saturation percentage for L0 is considered in Chapter 6 (Section 6.3.2.5).

Table 3.11: Mean pH (KCl) and acid saturation (AS) percentage at different treatment levels of dolomitic lime over three time periods (initial, after 1st harvest and at final harvest)

Applied lime (t ha ⁻¹)	pH initial	AS (%) initial	pH after 8 months	AS (%) after 8 months	pH trial end	AS (%) trial end	pH unit difference (I-F) ¹
L0	3.86	43.3	4.08	21.2	4.82	2.3	0.96
L2	3.86	42.2	4.18	16.8	5.25	1.4	1.39
L4	3.86	43.2	4.45	8.0	5.68	1.0	1.82
L8	3.86	43.6	4.69	4.6	6.06	1.0	2.20

¹(I-F) – initial - final

Calcium showed a positive association with applied N ($p=0.049$), P ($p=0.092$) and L ($p<0.001$) (Appendix 3.7). The amount of soil Ca increased significantly at each level of lime treatment with the greatest change being between L2 and L4 (difference = 103.1 mg Ca L⁻¹) (Figure 3.12). Calcium at L2 (445 mg Ca L⁻¹) represented the greatest change in yield from L0 (406 mg Ca L⁻¹). This could be the result of the crop reacting positively to the applied Ca. The addition of 2 t lime ha⁻¹ (800 kg Ca ha⁻¹) gave an increase in the soil test of 70 mg Ca L⁻¹ (1 mg Ca L⁻¹ = 11.4 kg Ca ha⁻¹ applied) on average between treatments for this soil type. The trial soils are mainly kaolinitic (subdominant illite) in the clay fraction and had a mean Ca saturation percentage of 61.14% over the trial duration. This varied from 56.16% (L0) to 64.85% (L8). Tisdale (1993) stated that these clay types are able to satisfy the Ca²⁺ requirements of most plants at saturation values of only 40 to 50%.

At the highest level of lime (L8) there was no evidence of a decrease in uptake of Mg and K as has been reported by numerous researchers (Hannaway et al., 1982; Smith et al., 1985; Grunes et al., 1992). This was probably due to the relatively low levels of Ca prevalent even at this lime rate on these soils. The interaction of Ca with P was reported by Ishizuka and Tanaka (1960) who maintained that Ca has the ability to stimulate the absorption of P (and K) at certain concentration ranges in nutrient solution experiments, although this is crop specific (Li et al., 2004).

Magnesium was moderately significantly associated with P ($p=0.072$) and highly significantly with lime ($p<0.001$) (Appendix 3.7). Magnesium was significant at all levels of lime application but as with Ca the greatest increase in Mg was with a change from L2 (93 mg Mg L⁻¹) to L4 (107 mg Mg L⁻¹) (Figure 3.13). The change in soil Mg was not of the same magnitude as Ca due to it being less strongly adsorbed to cation exchange sites (Foth, 2003). The mean Mg saturation percentage was 20.16% over the trial duration. The variation between L0 and L8 was not significant and the percentage Mg saturation remained almost constant throughout the lime treatment range, unlike Ca.

Magnesium has the potential to significantly decrease the uptake of K and Ca (Jakobsen, 1993). However, this was not evident even at the highest lime application rate as the Mg levels were probably still too low. Similarly, there was also no effect on P uptake by the increasing Mg content. The interactions of Mg with N and P were significant ($p=0.041$) (Sections 3.3.1.2 and 3.3.2.2, respectively).

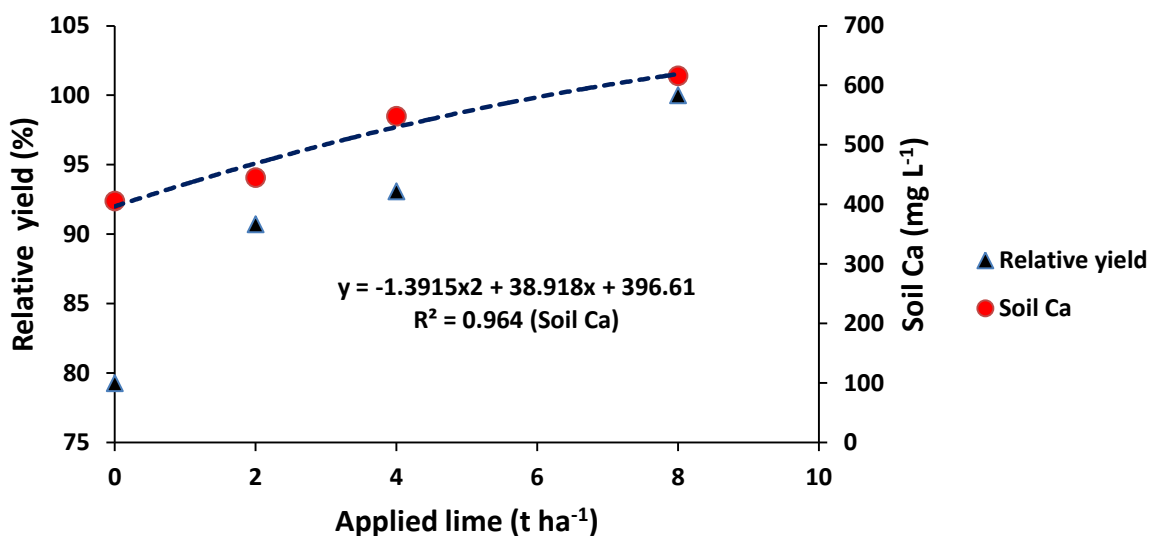


Figure 3.12: Mean (n=6) soil calcium (Ca) with different amounts of applied dolomitic lime and corresponding mean (n=6) relative yield over the three seasons (Soil Ca: CV% 16.1, l.s.d. 50.12, S.E.M. 80.94 at $p<0.05$).

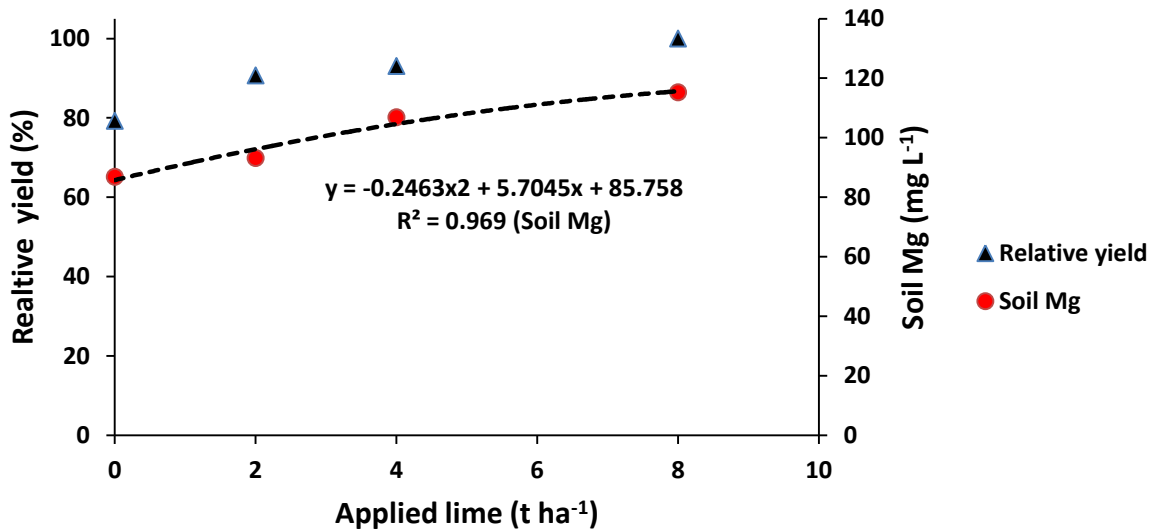


Figure 3.13 Mean (n=6) soil magnesium (Mg) with different amounts of applied dolomitic lime and corresponding mean (n=6) relative yield over three seasons (Soil Mg: CV% 17.9, l.s.d. 10.141, S.E.M. 18.011 at $p < 0.05$).

3.3.3.3 Leaf calcium and magnesium

Calcium in the leaf at 60 DAS ranged from 0.78 to 0.95%. The highest percentage was from the L4 treatment and the lowest from L0 (Figure 3.14). The 220 DAS sampling gave a higher leaf Ca percentage with a range from 0.93 to 1.2% Ca. Unlike the first sampling, the second sampling displayed a linear trend. The higher Ca in the leaves at harvest reflects that Ca is stored in the older leaves. Calcium is not a mobile element in plants and deficiencies are found in younger tissues (Hawkesford et al., 2012). With increasing age of the plant, Ca tends to increase. In general terms, Ca concentrations in healthy, most-recently matured leaves of vegetables will be from about 0.6 to 5.0% (Reuter and Robinson, 1997). The highest yield was obtained with 0.94% Ca at 60 DAS. A highly significant relationship was found between leaf Ca and N ($p < 0.001$) and lime ($p < 0.001$) (Appendix 3.8). A moderately significant interaction occurred between leaf Ca, N and P ($p = 0.093$) (Sections 3.3.2.2 and 3.3.3.2).

Magnesium in the leaf at 60 DAS ranged in a very narrow band from 0.30 to 0.32%. The highest percentage was from the L2 treatment and the lowest from L8 (Figure 3.14). The second leaf sampling was almost a replica of the first sampling results with a range from 0.32 to 0.33% Mg. The first sampling gave a slight negative trend with increasing lime while the second sampling displayed no trend across all treatments. Magnesium is a fairly mobile element in plants with deficiency symptoms mainly occurring in the older plant tissue

(Hochmuth et al., 1991; Hawkesford et al., 2012). Deficiency is usually found with leaf Mg from 0.10 to 0.15% (Reuter and Robinson, 1997). Some vegetable crops such as turnip, tomato and collards have a particularly high Mg requirement with a critical level close to 0.40% (Reuter and Robinson, 1997). Researchers have found that Mg availability and uptake by plants is severely restricted at a $\text{pH} \leq 5.4$ (Foth, 2003; Havlin et al., 2005), while Mg deficiencies can be induced by excessive K and $\text{NH}_4\text{-N}$ fertilisation (Harrison and Bergman, 1981; Plank, 1989, Hochmuth et al., 1993). The highest root yield was obtained with 0.30% Mg at 60 DAS. A significant relationship was found between applied N ($p=0.019$) and P ($p=0.010$) with leaf Mg (Appendix 3.8). The only significant interaction with Mg was that with N and time.

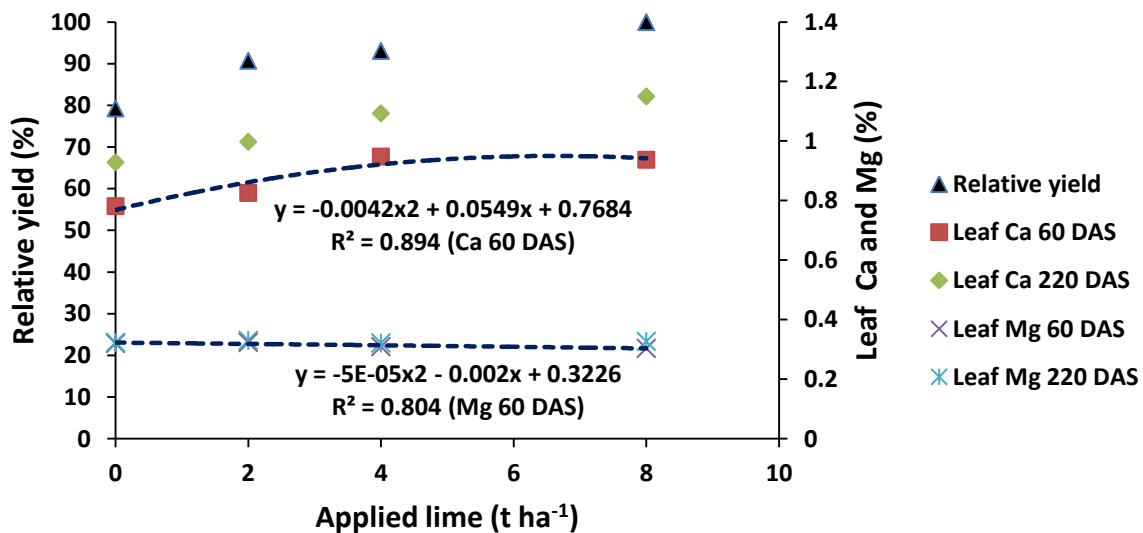


Figure 3.14: Leaf calcium (Ca) and magnesium (Mg) at two sampling times (60 and 220 days after sowing, (DAS)) with different amounts of applied dolomitic lime and corresponding mean relative yield over three seasons (n=6) (Leaf Ca% at (a) 60 DAS: CV% 16.2, l.s.d. 0.08166, S.E.M. 0.15558; and (b) Leaf Mg% 60 DAS: CV% 10.5, l.s.d. 0.01939, S.E.M. 0.03364 all at $p < 0.05$).

3.3.3.4 Root calcium and magnesium

Calcium in the root at harvest was positively significantly correlated with lime applied ($p < 0.001$) (Appendix 3.9) with Ca ranging from 0.19 to 0.21%. The highest root yield was attained with root Ca of 0.21%. Root Ca levels were significantly lower than those in the leaf. The RTFA (2010, 2015) gives the best target levels for roots to be forced for the production of chicons as 0.27-0.29% Ca. Even the highest root Ca from the current trial falls below this

range and suggests that for chicory production Ca levels are not the same as reported by the RTFA (2010, 2015) for chicon production as yields were similar to those obtained on average in Belgium and the Netherlands (Eurostat, 2012).

Root Mg did not show a significance response to N, P or lime applications (Appendix 3.9). Root Mg was relatively constant at about 0.13% across all treatments. The RTFA (2010, 2015) refers to a range of 0.125-0.150% as a target level and so the trial results are slightly above the minimum of this range at the highest rate of lime application.

3.4 Conclusion

Under irrigation management chicory responded well to applied N with yields of reasonable quantity and good quality being achieved with 160 kg N ha⁻¹. Higher N amounts (240 kg N ha⁻¹) produced slightly higher yields but this was at a cost, as root quality suffered with the number of diseased roots increasing to 15%. Yield tended to also show a good response to 80 kg N ha⁻¹ representing an 89.41% relative yield. In the warmer climate and under the soil conditions and irrigation management of the trial site, N use was greater compared to that found in the chicory growing areas of the cooler northern hemisphere, where much of the research on chicory growth has been carried out. Root length, width and herbage yield were significantly increased with the addition of the highest rate of N. However, as the N levels increased the leaf : root dry weight ratio and the harvest index decreased. Related to this the N utilisation efficiency (total dry yield / applied N) was lower. A leaf N concentration at 60 DAS of 3.74%, corresponding to 160 kg N ha⁻¹, was found to be optimum from a yield and root quality perspective. Values in the root below 0.9% N were associated with poor yields while 0.9 to 1.1% N gave average to good yields with limited root quality problems.

In contrast to the high requirement of chicory for N, response to P was much lower. With the addition of P, yield showed a positive but not significant ($p>0.05$) trend. This could be as a result of the initial soil P level of 23 mg L⁻¹ (at sample density 1.33 g mL⁻¹) that, in this soil, was not low enough to show a significant response. This also possibly indicates root chicory's ability to extract P efficiently. Also in contrast to that of N, it was established that root length and width were non-significant in the pooled analysis. The amount of leaf material was found to be significant at P80, while the leaf : root ratio, harvest index and the percentage of diseased roots did not show significant differences. Root chicory removed between 26.98 and 31.57 kg P ha⁻¹ in roots and leaves from the different treatments. Values of

0.40% P in the leaf at 60 DAS were associated with good yields. The highest yield was attained with root P of 0.22% P.

The field trial yields supported the reported synergism between N and P. There was a 6.5% increase in yield when the interaction between N and P was considered at the higher treatment levels. However, other confounding variables might have also played a role in this interaction.

Lime, like N, proved to be important for increasing the chicory harvest. It was observed that lime was responsible for increased yields in both the integrated and individual harvests and showed yield increases up to the highest rate applied of 8 t ha⁻¹ but this was significant only between L0 and L2. This was expected as the initial soil pH(KCl) was below 4.0 but was also likely due to a response to low initial soil Ca (160 mg Ca L⁻¹). The trial soils had a mean Ca saturation percentage of 61.14% while the mean Mg saturation percentage was 20.16% over the trial duration. The variation between L0 and L8 in both Ca and Mg saturation values was not significant and the percentage Mg saturation remained almost constant across the lime treatment range. The highest yield was obtained with 0.94% leaf Ca at 60 DAS when Mg in the leaf at 60 DAS ranged between 0.30 and 0.32%. The highest yield was attained with root Ca and Mg of 0.21 and 0.13%, respectively. Chicory seemed to be tolerant to the increase in pH and the subsequent effect on nutrient availability of other plant nutrients at L8 (pH never exceeded 7.0 in the trial).

The hypothesis that root chicory yield would respond significantly to N, P and lime at the 95% level of significance proved to be sound for N and lime but P levels did not give the expected yield response at the 5% level of significance.

CHAPTER FOUR

NITROGEN AND POTASSIUM FERTILISATION OF ROOT CHICORY (*Cichorium intybus* var. *sativum*)

4.1 Introduction

Nitrogen (N) and potassium (K) are elements of major importance to plant growth as they are two of the essential macronutrients. Nitrogen is a constituent of all proteins, chlorophyll, co-enzymes and nucleic acids in plants, while K functions in regulatory mechanisms such as photosynthesis, carbohydrate translocation and protein synthesis (Foth, 2003). An adequate amount of K is essential for the efficient use of N in crop plants. A balanced nutrition, especially with N and K due to their synergistic effect, has been explored by a number of researchers (Stromberger et al., 1994; Engels and Kirkby, 2001; Read et al., 2006; Brar et al., 2012). In contrast, high concentrations of K have antagonistic effects on the absorption of calcium (Ca) and magnesium (Mg) and these are affected by the plant species and environmental conditions (Fageria, 1983; Grunes et al., 1992; Tuma et al., 2004; Hannan, 2011).

However, limited work (Orchard and Van Rooyen 1953; Lachowski 1962; Patel et al., 1990; Baert and van Bockstaele 1993; Patel et al., 2000) has been done on root chicory to determine its yield response to different rates of applied N and K. Many other researchers studying root chicory for attributes other than fertiliser response have based their fertiliser applications on general fertiliser guidelines and the underlying quantitative basis for the applications used in most instances is not specified. Soil fertility, leaf and root analysis results under an irrigation management system are non-existent in the literature and therefore a trial was established to evaluate the response of root chicory to applied N and K and their interaction. The hypothesis that root chicory responds significantly to N and K application at $p < 0.05$ was tested.

4.2 Materials and methods

4.2.1 Site

The site was located in close proximity to the previous trial described in Chapter 3. Other than a small change in location (28.137056 S; 30.311861 E; 1 214 m.a.s.l.) the site conditions and history are the same as those described in Section 3.2.1. The soils were the same as described in Chapter 3 being low in clay (9.5%) and in residual N (0.068%) (Appendix 3.2).

4.2.2 Trial design

Due to the initial mean soil K being 123 mg L^{-1} it was decided to lower the soil K to accentuate the K response. A catch crop of oats (*Avena sativa* L.) was therefore planted in autumn 2012 without fertiliser, with the plant material removed from the trial site. This reduced the mean soil K prior to planting the field trial to $108.4 \text{ mg K L}^{-1}$, regarded by MAFF (1988) as an Index 2 K soil that would require 83 kg K ha^{-1} .

A 4 x 5 factorial design, with four rates of N (0, 60, 120, and 180 kg ha^{-1} , chosen to supplement those used in the trial reported in Chapter 3, as limestone ammonium nitrate (28% N)) and five rates of K (0, 50, 100, 150 and 200 kg ha^{-1} as potassium chloride (KCl) (52% K)), with three replications (60 plots in total), was used. The nomenclature used to describe the fertiliser application will subsequently be referred to as N0, N60, N120 and N180 for nitrogen and K0, K50, K100, K150 and K200 for potassium. Dolomitic lime (1.5 t ha^{-1}) was broadcast by hand 8 weeks prior to planting to decrease acid saturation percentage and increase Ca and Mg levels as determined from analysis of the mean exchangeable acidity and total cations. This was determined from the mean soil sample results according to the procedure as outlined by Manson et al. (2012) for the trial. Phosphorus as single superphosphate (10.5% P, 13% sulphur (S)) was broadcast at a rate of 20 kg P ha^{-1} as a starter application as recommended for soils with $<120 \text{ mg P L}^{-1}$ (Manson et al., 2012). Boron (B) was soil sprayed onto the soil at a rate of 1.5 kg B ha^{-1} and incorporated. A gross plot size of $3 \times 7 \text{ m}$ with a nett plot size of $2 \times 5 \text{ m}$ was used. Land preparation and planting was performed as for the N x P x L trial (Chapter 3) except that in 2014 the trial was planted in the autumn (1st April 2014) and harvested 260 days after sowing (DAS) on the 17 December 2014. Allowance for the cold period (15th June to 30th July) was given to allow the crop to respond, hence the later harvest date. Weeding, nematicide control and irrigation were almost the same as for the N x P x L trial. Differences were that weed control was carried out at 46 DAS when only a light hand hoeing was done due to low weed pressure at that time of the year. The 65 DAS weed control was not done due to limited weed competition. Irrigation in 2014 was modified to suit the decreased plant requirements during the initial part of the early autumn (April) growing season, but changed due to a lower water requirement during late autumn and winter. This was done according to soil tensiometer readings and it amounted to approximately 15 mm week^{-1} . At the start of warmer weather (about the middle of August)

weekly amounts were increased to 30 mm week⁻¹, pending rainfall. The spring plantings used this latter amount.

4.2.3 Sampling procedures and analysis

All sampling procedures and analyses were the same as given in Chapter 3. In addition, irrigation for the autumn planting (April) was done according to soil tensiometer readings and it amounted to approximately 15 mm week⁻¹. Furthermore a K balance sheet was established following work conducted by Lindemann et al. (1983), modified from N to K. This procedure takes into account the exchangeable K content in the 0-60 cm soil layer in September and the amount of added fertiliser K as inputs. The exchangeable soil K in (April/May), the unused fertiliser K, and the plant uptake are regarded as outputs. The apparent utilisation coefficient (AUC) of K fertiliser was obtained by measuring the difference between the K uptake of the fertilised (K_f up.) and unfertilised (K_{unf} up.) plots and dividing by the K fertiliser rate (K_r) (Equation 4.1):

$$AUC = \frac{(K_f \text{ up.} - K_{unf} \text{ up.})}{K_r} \times 100 \dots \dots \dots \text{Equation 4.1}$$

The apparent proportion of the absorbed K which was derived from the fertiliser (Kdff) was then calculated (Equation 4.2):

$$Kdff = \frac{(K_f \text{ up.} - K_{unf} \text{ up.})}{K_f \text{ up.}} \times 100 \dots \dots \dots \text{Equation 4.2}$$

4.3 Results and discussion

4.3.1 Nitrogen

4.3.1.1 Yield

As discussed in Section 3.2.2.1 the first season of planting had a lower plant population and resulted in a significantly lower yield as compared to the latter two seasons (Appendix 4.1). The field trial gave the highest yield at 180 kg N ha⁻¹ (Figure 4.1).

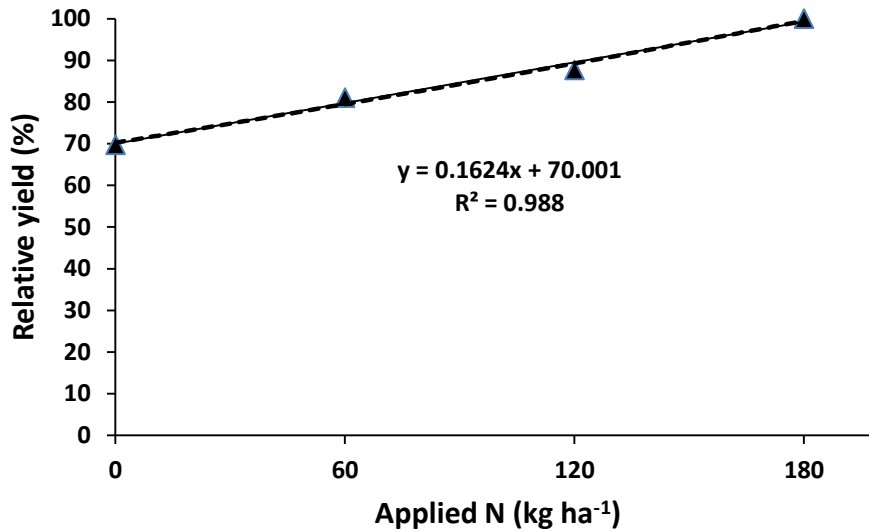


Figure 4.1: Mean relative yield of root chicory over three seasons (n=9) with different amounts of applied nitrogen (N) (CV% 18.2, l.s.d. 6.918, S.E.M. 7.455 at p<0.05).

As for the trial reported in Chapter 3 yields tended to show a good response to the lowest applied N treatment (60 kg N ha⁻¹) representing a mean 81.05% relative yield, compared to 69.73% for N0. The differences in yield and their significance are given in Table 4.1. With the addition of 180 kg N ha⁻¹ a 30.27% increase in wet yield was achieved from N0. Of this 11.32% was achieved with the application of 60 kg N ha⁻¹ and a similar increase was achieved between N120 and N180 (12.3%). The yield increase with the lowest rate of N applied is similar to that found in the N x P x L trial (Chapter 3) although not as pronounced due to the 20 kg N ha⁻¹ lower application. Root length and width (Table 4.2) and herbage yield were significantly increased (p<0.05) with the addition of nitrogen. Root width increased significantly with the addition of N60 and N180 while N120 produced a significant response to root length. Leaf yield showed significant responses to N60 and N180 additions. However, as the N levels increased the leaf : root dry weight ratio decreased, as in the N x P x L trial. Millard and Thomson (1989), working with apples, found that increasing N supply had no effect on root mass, but altered the leaf : root dry matter ratio as was also found in the current study (Table 4.3). Increasing levels of N fertiliser tend to delay root maturity (Limami and Laville, 1991) and can have a negative effect on disease susceptibility (Schober and Vermeulen, 1999). The number of diseased roots showed a slight increase with increased N application over the duration of the trial, up to 8% at N180, however, this was not significant (Table 4.3). Barloy and Fernez (1989) showed that high rates of N fertiliser reduced yields of Jerusalem artichoke (*Helianthus tuberosus L.*), another inulin containing crop.

Table 4.1: Mean yield of root chicory (n=9) over three harvests with different amounts of applied nitrogen (N)

Applied N (kg ha⁻¹)	Yield (t ha⁻¹)
N0	33.64 ^{a#}
N60	39.10 ^{ab}
N120	42.31 ^{ba}
N180	48.24 ^{bc}

- values with different superscripts are significant. CV% 18.2, l.s.d. 6.918, S.E.M. 7.455 at p<0.05.

The harvest index (root mass : total plant material mass) showed an increase with increasing N application (Table 4.3). Related to this the N utilisation efficiency (total dry yield/applied N, as defined by Bock, 1984) was lower and is similar to that found by Reerink (1992) for witloof chicory and Collins and McCoy (1997) and Belesky et al. (2000) for forage chicory.

Table 4.2: Root length and root width with different amounts of applied nitrogen (N) treatments over three seasons (n=9)

Applied N (kg ha⁻¹)	Root length (cm)				Root width (cm)			
	2012	2013	2014	Mean	2012	2013	2014	Mean
N0	24.6	24.7	25.0	24.8 ^{a#}	2.8	3.0	3.1	3.0 ^a
N60	24.0	24.2	25.5	24.6 ^a	3.2	3.4	3.4	3.3 ^b
N120	24.9	25.5	26.5	25.6 ^b	3.1	3.4	3.5	3.3 ^b
N180	25.2	25.9	27.2	26.1 ^b	3.7	3.9	4.0	3.9 ^c

- values with different superscripts within columns are significant. Root length: CV% 2.6, l.s.d. 0.7663, S.E.M. 0.6528. Root width: CV% 6.9, l.s.d. 0.2790, S.E.M. 0.2309 all at p<0.05.

Table 4.3: Root and leaf yields, leaf : root ratio, harvest index (root mass / total biomass), nitrogen utilisation efficiency and diseased roots averaged over three seasons (n=9) with different amounts of applied of nitrogen (N)

Applied N (kg ha ⁻¹)	Root yield (dry basis) (t ha ⁻¹)	Leaf yield (dry basis) (t ha ⁻¹)	Leaf : root (dry basis)	Harvest index	N utilisation efficiency (kg DM* kg ⁻¹ N)	Diseased roots (%)
N0	8.44	4.65 ^{a#}	0.55	0.65	–	0
N60	9.53	5.06 ^b	0.52	0.66	242	1
N120	11.74	5.29 ^b	0.46	0.69	142	3
N180	13.78	5.65 ^b	0.41	0.71	108	8

* DM – dry matter

- values with different superscripts within columns are significant. Leaf yield: CV% 3.2, l.s.d. 0.3142, S.E.M. 0.1638 at p<0.05.

Yield and quality depression with increasing N has also been observed in other crops such as maize, wheat, sunflower, sugar beet and potatoes (Bauer and Carter, 1986; Sowokinos and Preston, 1988; Blumenthal et al., 2008). When compared to the N x P x L trial (Chapter 3) the results are similar although this trial shows an increase in total biomass (leaf and root) as compared to the N x P x L trial. Personal observations during the growing period showed luxuriant leaf growth in the high N treatments, although crop yield did not decrease significantly as was found in the N x P x L trial. Leaf mass determination under field conditions, it must be added, was hampered by die back of leaves during the growing season, and wind. The variation in leaf biomass can be ascribed to the varying N levels in the leaves that give seasonal variations in photosynthetic capacity, resulting from a decrease in sink strength of the leaves for N allocation during plant development (Soja and Soja, 1995). Terry (1970) explained such rapid growth by the increase in N, which causes cells to divide and expand faster as N increases the number and size of the cells under favourable conditions.

At the highest application rates of N and K (N180 x K200) there was a non-significant 4.7% increase in yield compared to an N application of N180 used on its own (Table 4.1). With only N applied there was an initial increase in yield up to N120 followed by a decrease in yield to N180 (Table 4.4). Although not significant, the higher rates of K had a positive effect by encouraging better uptake of N and its utilisation and is a phenomenon that has been

reported for a variety of crops (Milford and Johnston, 2007; Römheld and Kirkby, 2010; Zhang et al., 2010, 2011).

Table 4.4: Effect of the interaction of applied nitrogen (N) and potassium (K) on wet yield (t ha^{-1}) of root chicory over three seasons (n=9)

Treatment (kg ha^{-1})	K0	K50	K100	K150	K200
N0	31.51	31.51	32.33	39.17	34.12
N60	38.28	33.11	37.41	41.31	45.37
N120	47.34	38.29	46.93	38.08	43.06
N180	41.88	51.51	48.72	48.55	50.52

CV% 18.2, l.s.d. 15.468, S.E.M. 7.455 at $p < 0.05$.

4.3.1.2 Soil nitrogen

In this trial, unlike the N x P x L trial (Chapter 3), soil N was non-significant with applied N. In addition, the interaction between N and K was also non-significant (Appendix 4.2). This can probably be ascribed to the relatively stable soil pH conditions (with minimal contribution from the application of LAN), unlike in the N x P x L trial where the addition of lime altered the availability of elements for the plants. The soil pH(KCl) in most plots fell between 5.5 and 6.0 for the duration of the trial (Appendix 4.3).

4.3.1.3 Leaf nitrogen

The first sampling at 60 DAS and the second at harvest gave differences of nutrient levels between the two time periods for each harvest (Figure 4.2). During the active growing period leaf N increased with applied N with a range from 3.28 to 3.62%, the latter being for N180 (the highest relative yield). At harvest (for the spring-planted chicory), growth was limited and N was almost constant at about 2.5 N%. The leaf % at N180 was similar to that obtained in the N x P x L trial (Chapter 3) at N160 (3.74% N).

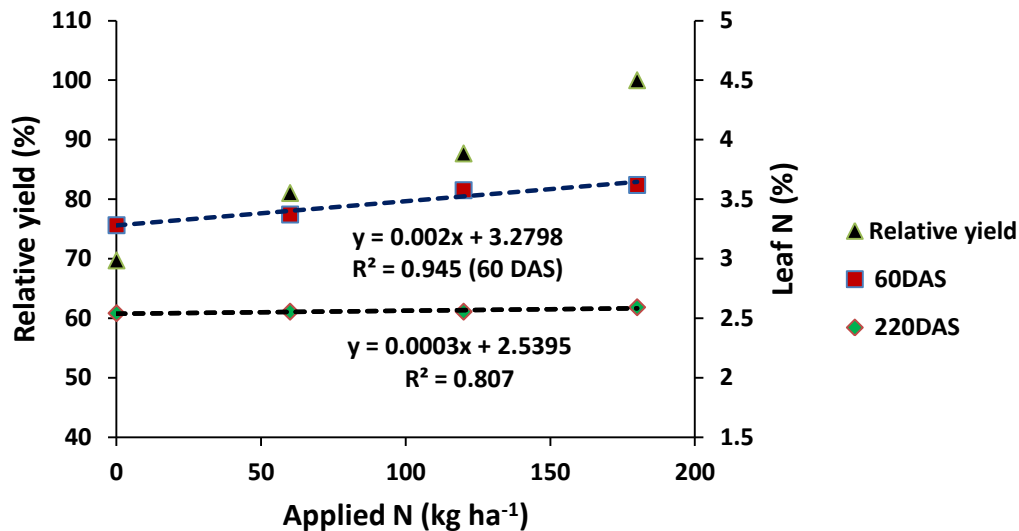


Figure 4.2: Mean leaf nitrogen (N) at two sampling times and relative yield with different amounts of applied N over three seasons (n=9) (Leaf N% at (a) 60 days after sowing (DAS): CV% 11.3, l.s.d. 0.2963, S.E.M. 0.3900; and (b) 220 DAS: CV% 9.6, l.s.d. 0.2018, S.E.M. 0.2473 all at $p < 0.05$).

A leaf N concentration range of 2.69 to 4.66% N was found for the 60 DAS sampling. Figure 4.3 illustrates a positive trend in yield with increasing leaf N. Significantly lower yields were recorded between 2.69 and 3.28% N at 60 DAS (Appendix 4.4) which is similar to the results from the N x P x L trial (Chapter 3). Root chicory experienced a yield reduction of 10% at a leaf N of 3.4% in keeping with previous findings (Chapter 3). This is slightly higher than the 3% value given by Campbell (2000) for crops in general. Below N60 (3.37% leaf N) yield was <80% of maximum and this is also somewhat higher than Reuter and Robinson's (1997) generalised value for crops of 2.75% N. Ćustić et al. (2003), on the other hand, reported that head chicory N values were fairly uniform at 2.92-3.69% for an average crop. No significant interaction between leaf N and K was found.

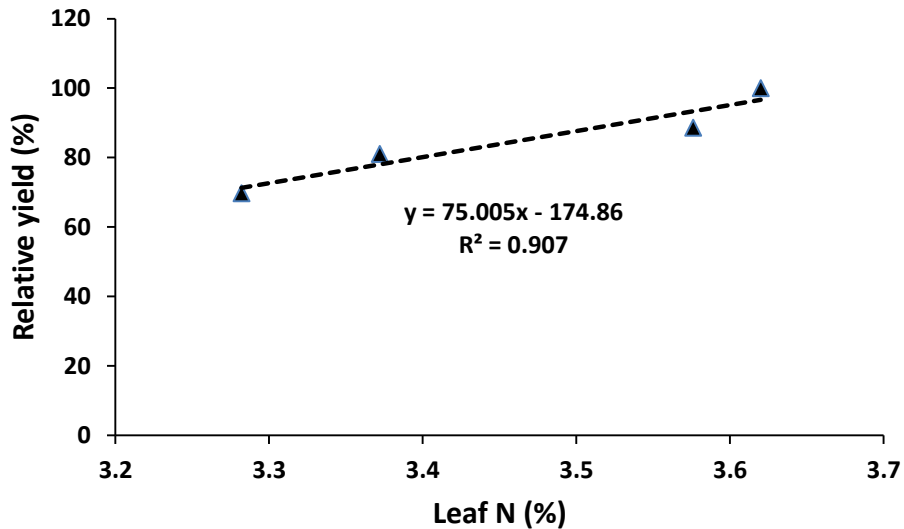


Figure 4.3: Mean leaf nitrogen (N) (n=9) at first sampling (60 days after sowing) over three seasons (CV% 11.3, l.s.d. 0.2963, S.E.M. 0.3900 at p<0.05).

4.3.1.4 Root nitrogen

There was a progressive linear increase in root N percentage with increasing N treatment although this was not significant (Appendix 4.5). No significant interaction between root N, applied K and combinations thereof was evident. The results for root N% were almost half the value of those found in the N x P x L trial and are lower than those advocated by the RTFA (2010, 2015) (Table 4.5). This could be a consequence of the length of time before harvest i.e., 265 DAS for the 2014 harvest.

Table 4.5: Root nitrogen (N) with different amounts of applied N for the 2014/2015 season (n=3)

Applied N (kg ha ⁻¹)	Mean root N (%)
N0	0.424 ^{a#}
N60	0.416 ^a
N120	0.482 ^b
N180	0.464 ^b

- values with different superscripts are significant. CV% 19.1; l.s.d. 0.0631; S.E.M. 0.0854 at p<0.05.

4.3.2 Potassium

4.3.2.1 Yield

There was a non-significant yield increase (Appendix 4.1) with the application of increasing amounts of K (Figure 4.4; Table 4.6). This could be because the initial K level in the topsoil (108.4 mg K L⁻¹) was not low enough to show a significant response to K and/or that the crop was obtaining K from the subsoil. The K x N interaction was also non-significant (Section 4.3.1.1). Root length and width was significant from K50 (Table 4.7) in the pooled analysis. The amount of leaf material was also found to be significant from K50. The leaf : root ratio showed an increase to K50 then decreased, the harvest index increased with higher K treatments while the number of diseased roots showed no difference between treatments (Table 4.8).

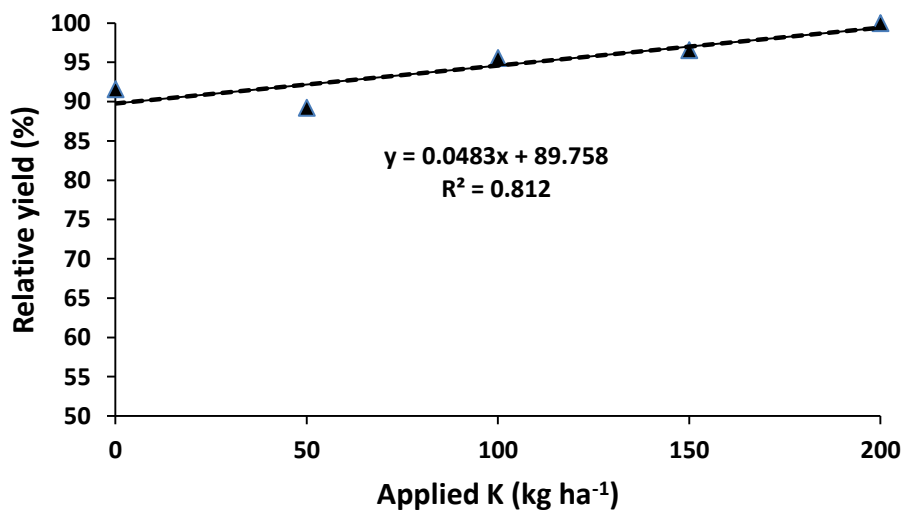


Figure 4.4: Mean relative yield of root chicory over three seasons (n=9) with different amounts of applied potassium (K) (CV% 18.2, l.s.d. 7.734, S.E.M. 7.455 at p<0.05).

Table 4.6: Wet yield of root chicory over three seasons (n=9) with different amounts of applied potassium (K)

Applied K (kg ha ⁻¹)	Yield (t ha ⁻¹)
K0	39.63 ^{ns#}
K50	38.61 ^{ns}
K100	41.35 ^{ns}
K150	41.78 ^{ns}
K200	43.27 ^{ns}

- ns = not significant. CV% 18.2, l.s.d. 7.734, S.E.M. 7.455 at p<0.05.

Table 4.7: Root length and root width as influenced by different amounts of applied potassium (K) per season (n=9)

Applied K (kg ha ⁻¹)	Root length (cm)				Root width (cm)			
	2012	2013	2014	Mean	2012	2013	2014	Mean
K0	22.8	22.9	24.0	23.3 ^{a#}	2.3	2.5	2.5	2.4 ^a
K50	24.0	24.4	24.9	24.4 ^b	2.8	2.9	3.1	2.9 ^b
K100	24.9	25.4	26.2	25.5 ^c	3.3	3.5	3.5	3.5 ^c
K150	25.7	26.2	27.3	26.4 ^d	3.5	3.8	3.9	3.8 ^c
K200	25.8	26.5	27.8	26.7 ^d	4.0	4.4	4.4	4.3 ^d

- values within a column with different superscripts are significant. Root length: CV% 2.6, l.s.d. 0.8567, S.E.M. 0.6528; Root width: CV% 6.9, l.s.d. 0.3119, S.E.M. 0.2309 all at p<0.05.

Table 4.8: Mean root and leaf yields, leaf : root ratio, harvest index (root mass / total biomass) and diseased roots (n=9) over three seasons with different amounts of applied potassium (K)

Applied K (kg ha ⁻¹)	Root yield (dry basis) (t ha ⁻¹)	Leaf yield (dry basis) (t ha ⁻¹)	Leaf : root (dry basis)	Harvest index	Diseased roots (%)
K0	9.01	4.39 ^{a#}	0.49	0.67	1
K50	8.97	4.93 ^b	0.55	0.65	1
K100	10.60	5.30 ^c	0.50	0.67	0
K150	11.29	5.44 ^c	0.48	0.68	0
K200	12.36	5.69 ^c	0.46	0.69	0

- values within a column with different superscripts are significant. Leaf yield: CV% 3.2, l.s.d. 0.3513, S.E.M. 0.1638 at p<0.05.

There was a poor yield response (especially in 2012) to applied fertiliser K probably as a result of there being sufficient available K in the soil (initial soil K (108 mg L⁻¹)). With no N applied there was an almost flat yield response to an increase in applied K. This could be due to the plant not reacting to applied fertiliser K but instead, it sought K from deeper in the soil. In 2013 there was an improved response to K indicating that the soil did not supply enough available K for the plant. The removal from the plots of the chicory leaves from the previous harvest could also have contributed to the lower available K in the soil. Without the application of K, the yield response was positive up to N120, but with increasing N the yield declined, but not significantly. The yield response compared to the 2012 harvest can probably also be attributed to a significantly increased plant population and the resulting depletion of soil K.

The slight difference between the 2014 and 2013 harvests is probably related to time of planting and growing period. The mean of the three harvests with the applied K treatments across all N rates shows that yield increased to the highest rate of K application (K200) and that the turning point for yield was not reached. There was also no significant difference between all treatments. However, where N was not applied it is evident that there is hardly any change (3.44% difference) in relative yield from K150 to K200 (Figure 4.4). A possible explanation for this is that in the N0 treatment insufficient K may have led to reduced N uptake especially in the K0 and K50 treatments. From K100 to K150 there is sufficient K to

allow for a yield increase as N is utilised better from the mineral N pool but yield then declines due to insufficient N being utilised from the mineral N pool (Hagin et al., 1990; Liu et al., 1997; Milford and Johnston, 2007).

The significant ($p < 0.05$) decrease in mean root mass in the N0 treatment at the K200 application rate is likely a result of the lack of N, which is required to increase root mass. All the other N treatments show an increase in root mass at K200. Lack of K may lead to reduced N uptake and thus less developed roots. The N utilisation efficiency is thus increased by optimal K nutrition (Milford and Johnston, 2007; Zhang et al., 2010, 2011). At lower N fertiliser application rates, K application is not as critical as at high N application (Ledgard and Saunders, 1982; Gething, 1993).

Many crops (e.g. wheat, sunflower, rice and pearl millet) respond favourably when both N and K are applied, due to their synergistic effect (Pettersson, 1984; Hagin et al., 1990; Westermann et al., 1994; Milford and Johnston, 2007; Zhang et al., 2010, 2011).

In the current study the interaction of N x K gave the highest yield of 51.51 t ha^{-1} at N180 and K50 but this was not significantly different to the other N x K combinations. This could be a result of the root chicory using soil K more efficiently and from a greater depth than crops that do not produce a long storage taproot. This is further discussed in Section 4.3.2.2.

4.3.2.2 Soil potassium

Topsoil

Potassium treatments had a highly significant effect on soil K ($p < 0.001$) (Appendix 4.2) with a positive linear trend (Figure 4.5).

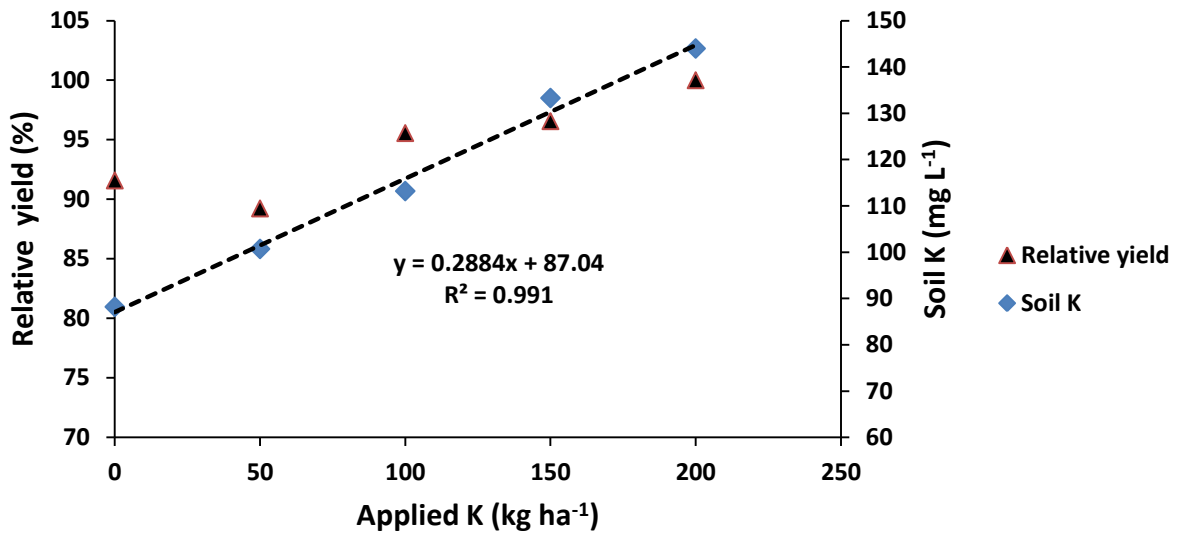


Figure 4.5: Soil potassium (K) with different amounts of applied K and corresponding relative yield over three seasons (n=9) (Soil K: CV% 19.9, l.s.d. 23.98, S.E.M. 23.05 at $p < 0.05$).

Topsoil K results showed a significant correlation with N application ($p=0.007$). At the higher application rates of N, topsoil K decreased over the three years, with increasing yield, at all K application rates (Figure 4.6). After all three harvests there was a decrease in available topsoil K, with increasing N application, probably as a result of excessive N fertilisation that led to increased K leaching (Alfaro et al., 2003) due to the enhanced transport of the K^+ ion with the NO_3^- anion, especially in this soil with low clay and a low cation exchange capacity. Chicory being a deep-rooted crop would in all likelihood be able to utilise this leached K and N. The available topsoil K response to leaf removal can be observed when the 2013 and 2014 harvests are compared (Figure 4.7). Soil incorporation of the previous harvest's chicory leaves is clearly beneficial for K nutrient supply and helps to slow down K loss. There was no interaction between the N and K application effects on soil K. The effect of the application of K across all N treatments was to increase topsoil K and the difference between the 2013 and 2014 results again emphasises the importance for topsoil K of leaf incorporation.

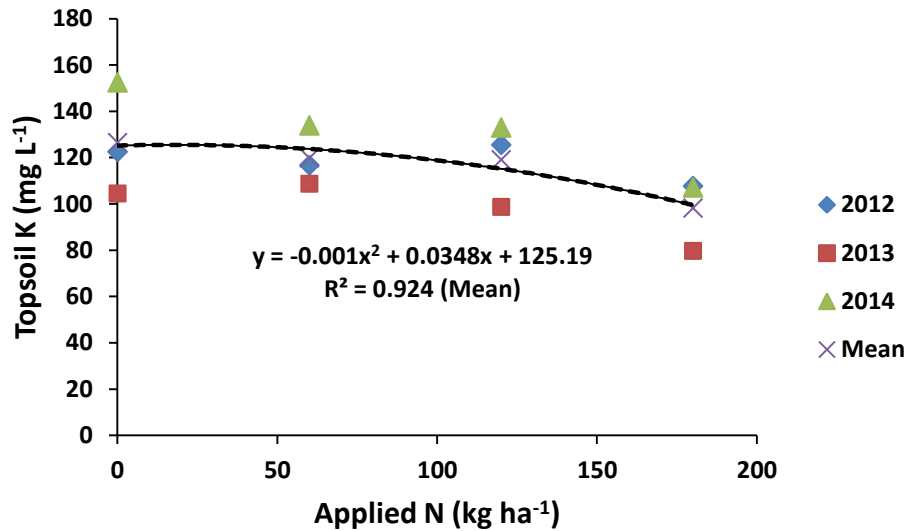


Figure 4.6: Mean topsoil potassium (K) (n=9), and as three individual seasons (n=9) with different amounts of applied nitrogen (N) and all levels of K (CV% 19.9, l.s.d. 21.45, S.E.M. 23.05 at $p < 0.05$).

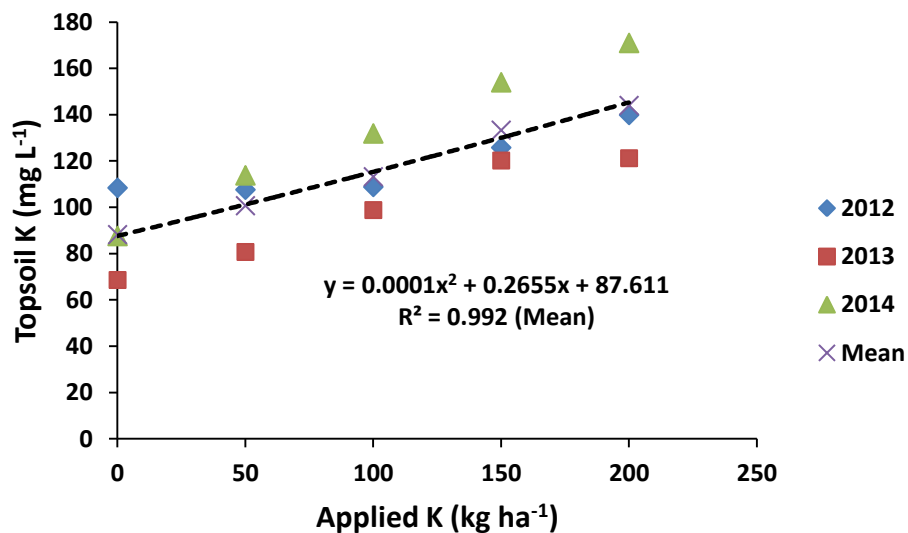


Figure 4.7: Mean topsoil potassium (K) (n=9), and as three individual seasons (n=9) with different amounts of applied K and all levels of nitrogen (N) (CV% 19.9, l.s.d. 23.98, S.E.M. 23.05 at $p < 0.05$).

Subsoil

The overall subsoil mean K was 55.3 mg L⁻¹ which is regarded as low. Manson et al. (2012) working with maize have indicated that subsoils lower than 100 mg K L⁻¹ should receive a higher topsoil K fertilisation rate than subsoils with greater than this amount. They intimate

that possibly this principle should be applied to other deep-rooted crops as well but that further research is required.

Samples taken at a depth of 20-60 cm showed a significant ($p=0.014$) (Appendix 4.2) trend of depletion in available subsoil K at each application rate (Figure 4.8). The K200 application ranged from 58.7 to 67.3 mg L^{-1} while the K0 treatment had the lowest subsoil K with a range from 37.8 to 60.2 mg L^{-1} .



Figure 4.8: Subsoil potassium (K) (20-60 cm depth) with different amounts of applied K and all levels of nitrogen (N) for each season (n=9) (CV% 29.3, l.s.d. 14.46, S.E.M. 16.20 at $p<0.05$).

The influence on mean subsoil K of the different N application rates across all rates of applied K is illustrated in Figure 4.9. There was a significant decrease ($p<0.05$) in subsoil K with increasing N application, especially from N120 to N180. In contrast, there was a non-significant increase in subsoil K with increasing K application rate at all N rates.

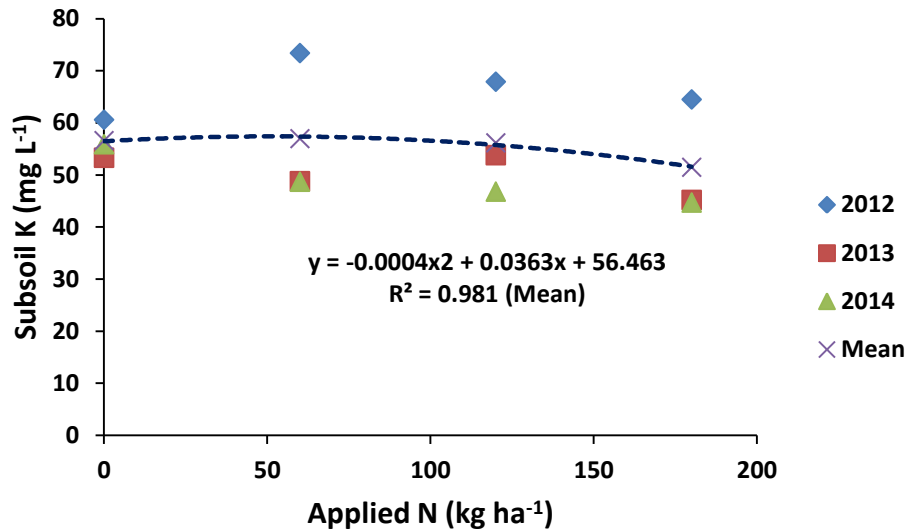


Figure 4.9: Mean subsoil potassium (K) (20-60 cm depth) (n=9), for each season (n=3) with different amounts of applied nitrogen (N) and all levels of K (CV% 29.3, l.s.d. 12.93, S.E.M. 16.20 at p<0.05).

The chicory plant has a long taproot (Hafner and Kuzyakov, 2016) and can therefore penetrate the subsoil. Substantial leaching losses of K can occur on coarse sandy soils due to their low cation exchange capacity (Munson and Nelson, 1963). The soil at the trial site consisted of 80.5% sand and it was therefore expected that down-profile movement of K (Askegaard et al., 2003) under irrigation would occur (Johnston and Goulding, 1992; Simmelsgaard 1996; Alfaro et al., 2003). These soils have more clay in their subsoils, and a build-up of K in the lower layers of the soil is frequently found. The initial subsoil K prior to the commencement of the trial supports the results of Miles and Farina (2014) that described 30 years of soil fertility work on maize at the DARS and noted a build-up of subsoil K over time.

However, on the trial site an increasing amount of K in the subsoil was not measured due in all probability to the chicory crop utilising the available K in the profile. The chicory crop was found to be reducing the amount of subsoil K over time especially from the low K treatments (K0 and K50).

The depletion of the subsoil reserves over the three harvests might explain why the yield graphs have not reached a maximum with the N and K treatments applied. If the applied K had been larger the interaction with N could have produced higher yields and possibly the turning point would have been established.

It is suggested that at the highest N application rate there is more efficient use of K from the topsoil which is promoted by N uptake by the plant and it is likely that the crop is not utilising much subsoil K. Conversely, when N supply is low the crop depletes the subsoil K over time.

There is little work on the uptake of subsoil K in the literature for deep rooted crops. However, Witter and Johansson (2001) near Uppsala, in central Sweden, used different green manure crops including chicory to determine the total K uptake and the proportion of K taken up from the subsoil. No additional K was applied. Their findings suggested that crops with a strong primary root system, such as chicory, obtain a considerable amount of their total K from the subsoil. In their study 80 kg K ha⁻¹ from the subsoil was taken up by chicory, which was about twice that of the other crops that were compared. Haak (1978) and Kuhlmann (1990) in Sweden and Germany, respectively, have indicated that spring-sown wheat (*Triticum aestivum* L.) obtained between 30 and 40% of its K from the subsoil with roots that extended to 1 m. Furthermore, it has been reported that some plants such as lucerne (*Medicago sativa* L.) have a rooting system that extend to 2 m (Evans, 1978) and have the ability to take up 200 kg K ha⁻¹ yr⁻¹ (Lee and Metson, 1977).

Sampling the topsoil only might not be adequate to determine the K nutrient requirement of root chicory. High subsoil K (>100 mg L⁻¹) might provide an additional supply of K and would have to be balanced with the topsoil amount so that a better nutrient use efficiency can be obtained. Sandy topsoils previously fertilised with K for crops without a well-developed root system often have high subsoil K contents, especially those soils with more subsoil clay and so recommendations based on topsoil samples will overestimate K requirement (Manson et al., 2012). Sandy soils that lack a clay-rich subsoil do not have the cation exchange capacity for build-up and maintenance of adequate soil K, making annual applications necessary (DEFRA, 2010). With sub-optimal fertilisation of K in the topsoil, pressure is put on subsoil K reserves when deep-rooted crops are grown, as they have the ability to use plant-available K from a much greater depth than other crops (Witter and Johansson, 2001) and ultimately subsoil K also becomes depleted.

4.3.2.3 Leaf potassium

Yield results over all three seasons showed a slight negative trend with increasing leaf K% at the first leaf sampling (Figure 4.10). Values of 4.2 to 4.5% K were associated with good

yields, as compared to others in the trial, at the 95% confidence level (Appendix 4.4). The range of leaf K during this active growth phase varied from 3.97% (K0) to 4.60% (K200) averaged over the three years with applied K (Figure 4.11). The second leaf sampling mean ranged from 3.59% (K0) to 4.13% (K200) and also varied significantly with added K.

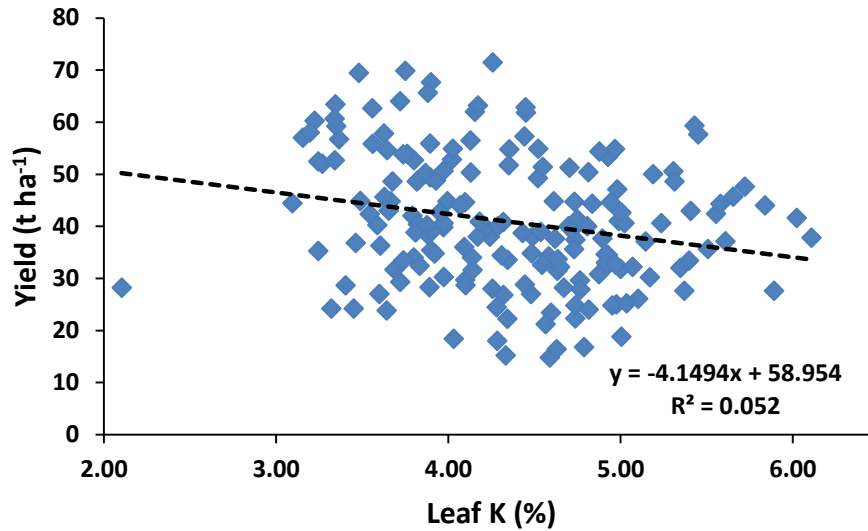


Figure 4.10: Mean (n=9) leaf potassium (K) at first sampling 60 days after sowing and yield over three seasons.

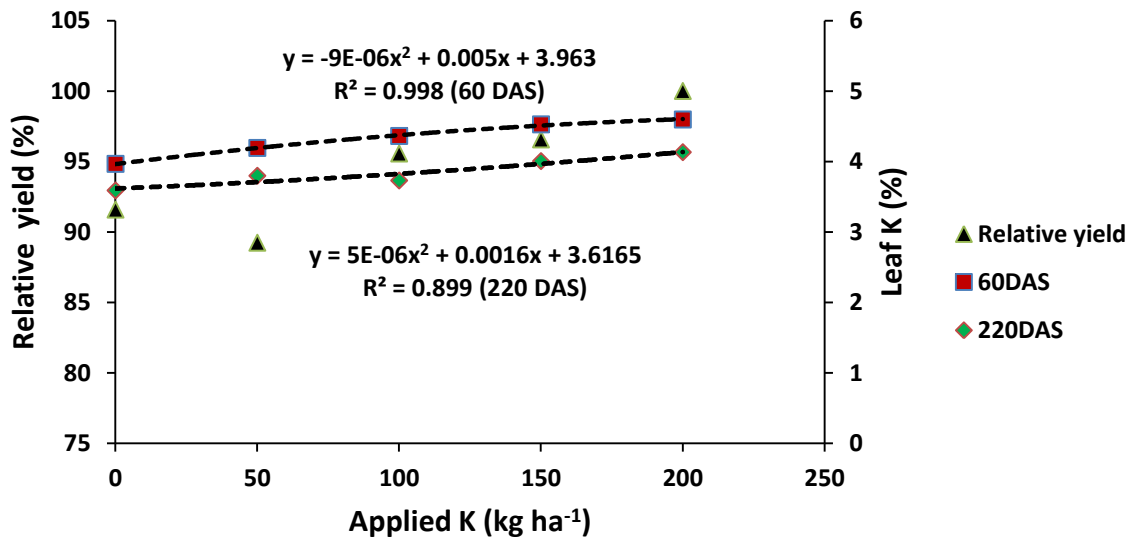


Figure 4.11: Mean leaf potassium (K) at two sampling times and relative yield with different amounts of applied K and corresponding relative yield (n=9) over three seasons (Leaf K% at first sampling 60 days after sowing (DAS): CV% 10.7, l.s.d. 0.4029, S.E.M. 0.4610; and (b) 220 DAS: CV% 11.2, l.s.d. 0.4036, S.E.M. 0.4293 all at $p < 0.05$).

Whereas leaf K at 60 DAS was significant with applied K ($p=0.002$) the 220 DAS leaf K was also significant with applied N ($p=0.046$). The autumn-planted trial (2014) showed lower leaf K as the sampling was done in May when temperatures were cooler and plant growth was slowing. This trial (2014) was harvested in December when soil temperatures were favourable for growth, and because of the plants biennial nature they continued to produce vigorous leaf growth producing leaf K results that were higher than the first leaf sampling. The plant K requirement is usually highest when it is in its early growth phase and declines with age. The results from the trial seem to correspond fairly well with those of Ćustić et al. (2003) working with leafy chicory. They found in their experiments that K in head chicory ranged from 3.27 to 5.16% K in the plant tissue at 60 DAS whereas in this trial, they ranged from 3.15 to 6.1% K.

Leaf K decreased, especially at the highest level of N, suggesting that due to the increase in yield the dilution effect played a role (Jarrell and Beverly, 1981) resulting in the lower leaf K. (Figure 4.12). The soil results (Section 4.3.2.2) showed that increasing application of N decreased K in the topsoil. Interactions between leaf K and applied (N x K) were non-significant at the 5% level of significance.

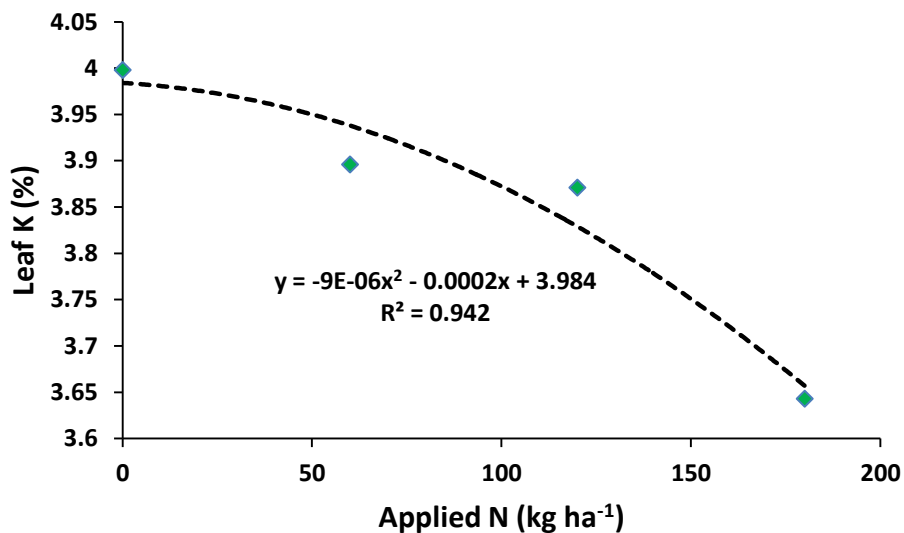


Figure 4.12: Mean leaf potassium (K) at harvest (n=9) with different amounts of applied nitrogen (N) (CV% 11.2, l.s.d. 0.2454, S.E.M. 0.4293 at $p<0.05$).

4.3.2.4 Root potassium

Potassium application had a significant effect ($p=0.010$) (Appendix 4.5) on K in the root (Figure 4.13) which ranged from 1.04 to 1.32%. The highest yield was attained with root K of

1.24 %. The RTFA (2010, 2015) referred to work done by Dutch researchers (Sarrazyn and Deckers, 1991) that suggested roots at harvest should have a target amount of between 1.5 to 2% K for adequate chicon production. The trial results did not achieve that target minimum and that is perhaps the result of the longer growing period of the 2014 trial. However, root K results from the N x P x L trial (Chapter 3) which was grown for a shorter duration (220 DAS) ranged from 1.39 to 1.48% K with applied N and thus also did not make the Dutch criteria possibly due to differences in clay percentage and soil type of the Dutch site compared to the present trial. Potassium levels in the root were not significantly associated with applied N or a combination of applied N and K (N x K interaction).

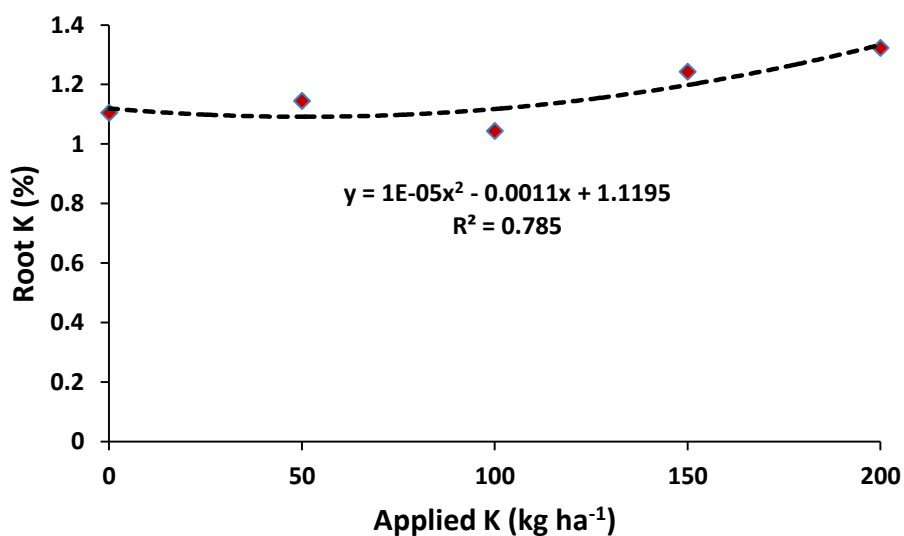


Figure 4.13: Root potassium (K) with different amounts of applied K for the 2014 season (n=3) (CV% 16.8, l.s.d. 0.1629, S.E.M. 0.1971 at p<0.05).

4.3.2.5 Potassium balance sheet

The exchangeable K in the 0-60 cm layer at planting time averaged 429 kg K ha⁻¹ (Table 4.9). After harvest, this fell to 348 kg K ha⁻¹, in the 0 K treatments. The mean difference between planting and harvest exchangeable potassium was 46 kg K ha⁻¹ in the 0-20 cm layer, and 81 kg K ha⁻¹ in the 0-60 cm layer in plots receiving no fertiliser K (Table 4.9). The decrease in soil K was much less than the K absorbed by the chicory (Table 4.10). Uptake of subsoil K from below 60 cm or replenishment of exchangeable K from the non-exchangeable pool must account for this difference and could justify the use of nitric K analysis to determine the reserve K pool. In turn, the soil exchangeable K remained relatively constant even with a high K uptake by the plant. It is important to note that the K content of the leaves was 255 kg

K ha⁻¹ in the K0 plots (Table 4.10). This amount is higher than the mean 80 kg K ha⁻¹ decrease of exchangeable soil K in the 0-60 cm layer and would be returned to the soil. It may also compensate for the root K uptake which was 134 kg K ha⁻¹ in the K0 plots. Root chicory acts as a nutrient pump (Schroth and Sinclair, 2003); it absorbs subsoil K and recycles a part of it as green manure to the soil surface. As a result, the root chicory did not exhaust the supply of K in the upper part of the soil. The difference between total input and output from 236 to 289 kg K ha⁻¹ found in the K balance sheet probably represents mostly subsoil K absorbed by the plant from deeper than 60 cm (Table 4.10).

In soils with high available K, fertiliser K makes a low contribution to root chicory nutrition. The fertiliser Kdff value represents the proportion of K uptake which is derived from fertiliser. In the present trial, the Kdff values were 0, 10.94, 21.95 and 20.56% for the 50, 100, 150 and 200 kg K ha⁻¹ application rates, respectively (Table 4.11). The soil K dominated the K nutrition of the root chicory and this may explain the relatively small effects of fertiliser K on yield and root quality.

The apparent utilisation coefficient (AUC) is the percentage of fertiliser K absorbed by root chicory as a proportion of the fertiliser K added. These values varied from 0 to 60% within the trial (Table 4.11).

The K balance sheet shows that it is possible to not apply K without depleting exchangeable K if the soil has high exchangeable K content in the subsoil. It has been suggested by Manson et al. (2012) that 250 kg K ha⁻¹ be regarded as the lower limit for a subsoil in order to be considered as having adequate K for maize and possibly other deep-rooted crops. The soil at the trial site had an initial mean subsoil K of 132 kg ha⁻¹ which would be considered to be low by this criterion. As a result, it would appear to be necessary to compensate for the K removal by an equivalent fertiliser rate to maintain the soil K content at an adequate level for the following crop.

However, the K content of the leaves returned to the soil surface would be able to compensate for root K uptake, mitigating against the need for added fertiliser K. Removing chicory leaf material from the plots, as was done in 2013, imposed a negative result on soil K reserves resulting in an increased K requirement.

Table 4.9: Mean (n=9) and total exchangeable potassium (K) content in different soil layers sampled at planting and harvest over three seasons

Treatment	Planting K (kg ha ⁻¹)				Harvest K (kg ha ⁻¹)			
	0-20 cm	20-40 cm	40-60 cm	Total	0-20 cm	20-40 cm	40-60 cm	Total
K0	222.1	114.8	91.8	428.6	176.4	92.6	78.8	347.8
K50	210.0	124.0	92.4	426.4	201.4	110.4	85.2	397.0
K100	264.3	120.6	111.4	496.4	226.6	104.4	81.0	412.0
K150	290.2	141.8	132.6	564.4	266.6	123.8	113.6	504.0
K200	336.0	139.6	120.2	595.8	288.0	121.8	110.8	520.6

Table 4.10: Mean (n=9) root yield, and potassium (K) concentrations and K uptake by leaves and roots of root chicory with different amounts of applied K

Applied K (kg ha ⁻¹)	Root yield (dry basis) (kg ha ⁻¹)	Root K concentration (dry basis) (%)	Root K uptake (kg ha ⁻¹)	Leaf yield (dry basis) (kg ha ⁻¹)	Leaf K concentration (dry basis) (%)	Leaf K uptake (kg ha ⁻¹)
K0	9 010	1.105	133.55	5 560	3.965	255.15
K50	8 970	1.145	137.77	5 153	4.191	249.95
K100	10 600	1.204	171.19	5 363	4.361	270.69
K150	11 290	1.243	188.24	5 970	4.526	312.73
K200	12 360	1.323	219.35	5 196	4.595	276.33

Table 4.11: Mean (n=9) potassium (K) balance sheet of root chicory with amounts of applied K

Applied K	K-input [#]	Total K uptake	Unused fertiliser K	K-output*	K-difference [§]	AUC	Kdff
		(kg ha ⁻¹)				%	
K0	429	320	None applied	668	239	None used	None used
K50	476	320	50	765	289	0	0
K100	596	355	65	832	236	35	10.94
K150	714	410	60	974	260	60	21.95
K200	796	403	117	1041	245	42	20.56

[#] K-input = planting + K rate

* K-output = harvest-K + total K-uptake + unused K

[§] K-difference = K-output – K-input

AUC = apparent utilisation coefficient

Kdff = the proportion of K uptake derived from fertiliser

4.4 Conclusion

From the analysis over the three harvests the hypothesis that root chicory responds significantly to N and K application is only partially accepted as root chicory responded to N but not K at $p < 0.05$ under the prevailing trial conditions.

4.4.1 Nitrogen

In all instances the beneficial effect of N contribution to yield was evident and supports work from the previously reported trial (Chapter 3). The harvest index which measures the root yield in relation to the biological yield gave a larger increase in leaf than in root yield at the highest amount of applied N. However, the N utilisation efficiency (total dry yield/applied N) declined with higher N treatments.

Nitrogen treatments had a significant effect ($p < 0.05$) on K in the soil. As the N application rate increased, the soil K decreased at all sampling times. The mean range for leaf N, without applied K, was from 3.4 to 3.7% and was positively correlated to yield. There was a moderately significant correlation between root N content and applied N but no association between root N and applied K or applied (N x K) for the 2014/2015 (autumn planting).

4.4.2 Potassium

In contrast to N, K treatments showed a non-significant trend of increasing yield with K applied. It is likely that the root chicory with its deep rooting system was able to extract K from deeper in the soil and thus the response to added K fertiliser was not pronounced. Leaf yield response to K was not as clear as with N and tended to decrease ($5.44 \text{ t DM ha}^{-1}$) at the highest level of K200 from $5.69 \text{ t DM ha}^{-1}$ at K150. Without applied N, a maximum wet root yield of 39.17 t ha^{-1} with leaf K of 4.8% was obtained at K150. A negative yield correlation to increasing leaf K was observed over all harvests. The harvest index increased with higher K treatment, the result of a decrease in leaf mass as compared to root yield. The K concentration of roots was significantly increased by K fertilisation. Root K decreased with increasing N, especially at the higher N treatment levels.

The maximum yield without N corresponded to a mean topsoil value of 133 mg K L^{-1} for K150 plots. Treatments involving K with all N application rates did not reach maximum yield. Higher K application rates could have resulted in the turning point being found for these conditions and further investigation is required.

The initial mean subsoil K was 132 kg ha^{-1} (66 mg L^{-1}) in 2012 and this decreased over time. There was significantly less K ($p < 0.05$) in the low K treatments in 2014 as compared to 2012. In the higher K treatments, the depletion of the subsoil K was not as great, probably as a result of the crop obtaining most of its K requirement from the topsoil and added fertiliser. It is suggested that more efficient use of K in the topsoil is promoted by N uptake by the plant in the higher N treatments. It is likely that the crop is not utilising much subsoil potassium under such conditions compared to when N is low which leads to a more rapid depletion of subsoil K over time.

Sub-optimal K fertilisation of deep rooted crops will put stress on the subsoil K reserves in soils low in exchangeable K ($< 100 \text{ mg L}^{-1}$), ultimately depleting subsoil K. Sampling the topsoil only to determine the K nutrient requirement will probably not be adequate for root chicory. Practically the depth of soil sampling for this deep-rooted crop should be revised from the current 0-15 cm to one that includes deeper sampling to account for the subsoil K thereby improving the K recommendation.

The K balance sheet showed that less than half of the fertiliser K, on average, was absorbed by the root chicory. The K derived from fertiliser in the whole plant was affected by the fertilisation rates. The Kdff (the proportion of K uptake which is derived from fertiliser) varied from 10.94 to 21.95%, illustrating that soil K was more important for root chicory nutrition. The K uptake by the leaves, which should be returned to the soil at harvest, is able to compensate for the decrease of soil K in the upper 0–60 cm and for the root K uptake. An impoverishment of the soil K is likely to occur over the short term, if leaves are utilised and not returned to the soil. The determination of exchangeable soil K in the topsoil alone will underestimate the K availability for root chicory when the subsoil is high in exchangeable K. Soils that have topsoils with a medium to coarse sandy texture with low available-K reserves, and that do not have a clay-enriched B-horizon, need to be fertilised with K on an annual basis. A split application, at planting and at 60 DAS should benefit the crop under irrigation management.

In this trial, the N x K interaction was not significant. However, the trends suggest that the fertiliser N rate should not be established without considering the fertiliser K rate. When no K fertilisation was used, a relatively low 60 kg N ha⁻¹ was sufficient for maximum yield. However, when the K fertilisation was high (150-200 kg K ha⁻¹), higher rates of N fertilisation was necessary to ensure adequate N uptake.

CHAPTER FIVE

BORON FERTILISATION OF ROOT CHICORY (*Cichorium intybus* var. *sativum*)

5.1 Introduction

The amount of literature on the response of crops to boron (B) is large. However, the literature on B and chicory (*Cichorium intybus* var. *sativum*) is very scarce, largely anecdotal and generally not based on quantitative research findings (MAFF, 1988; Baert and Bockstaele, 1993; Shorrocks, 1997).

A general average B concentration of about 10 mg kg⁻¹ is found in the silicate minerals of the Earth's crust (Krauskopf et al., 1972). The concentration of total B in soils is reported by Mengel and Kirkby (2012) as being in the range from 20 to 200 mg kg⁻¹ with the available concentration also differing widely in different soils. Boron occurs in aqueous solution as boric acid B(OH)₃ which is a weak monobasic acid that acts as an electron acceptor or as a Lewis acid (Parfitt, 1976). Boric acid is the major form of B found in soils (Raven, 1980) with H₂BO₃⁻ predominant only above pH 9.2 (Lindsay, 1973). The soil chemistry of B is relatively simple, unlike some other nutrient elements, as it does not change by volatilisation or oxidation-reduction reactions in the soil. However, the interactions of B with soil organic matter are complex, and difficult to quantify.

Warington (1923) reported that B was an essential element for cell structure and today it is accepted that it is a micronutrient needed for normal development and growth of plants and animals (Goldbach and Wimmer 2007). Sillanpää (1982) and Gupta (1993) have indicated that B deficiency is one of the major constraints to crop production and Shorrocks (1997) refers to 80 countries and 132 crops in which deficiency symptoms have been reported. Boron deficiency is regarded as the second most important micronutrient limitation to crop growth, after zinc, worldwide (Gupta, 1980; Shorrocks, 1997).

Sutradhar et al. (2016) summarised research findings on plant available B intimating that boric acid is a neutral molecule not attracted to soil particles and organic matter and thus is readily leached from soils with excess rainfall and irrigation. Coarse-textured soils with low organic matter are most prone to leaching and B may reach the subsoil in a short period of

time (Silva et al., 1995). It is therefore expected that a response will be evident on sandy textured soil (Alleoni and Camargo, 2000; Saltali et al., 2005).

Soils which typically show B deficiency are those that are highly leached and/or have developed from calcareous, alluvial or loessial deposits (Takkar et al., 1989; Razzaq and Rafiq, 1996; Borkakati and Takkar, 2000). Factors which contribute to soils being deficient in B include liming, high pH, coarse texture, low organic matter content, drought, more nutrient uptake than application, and the use of fertilisers low in micronutrients (Dregne and Powers, 1942; Elrashidi and O'Connor, 1982; Takkar et al., 1989; Goldberg and Forster, 1991; Niaz et al., 2002, 2007; Rashid and Rayan, 2004; Mengel and Kirkby, 2012).

Monocotyledons have a lower B requirement than dicotyledons such as chicory (Berger, 1949; Tanaka, 1967). Much of the B in soil is not plant-available as it is adsorbed by soil colloids and plants can only utilise the B in soil solution, which usually is less than 5% of the total B (Gupta, 1968; Ryan et al., 1977; Keren et al., 1985; Shorrocks, 1997).

Brown and Shelp (1997) and Brown and Hu (1998) concluded that B mobility is plant-species specific and the optimum fertilisation strategy should take cognisance of this. Root crops such as sugar beet, beetroot and turnip are reported to be susceptible to B deficiency (MAFF, 1988; Shorrocks, 1997).

Shorrocks (1997) suggested B application rates for a wide variety of crops and the majority of dicotyledonous plants require between 0.5 and 3.5 kg B ha⁻¹. This application rate, divided into 0.5 kg B ha⁻¹ increments, was used as the basis for the trial.

Dunn et al. (2005) reported mixed results with soil versus foliar B applications on rice yield. Roberts et al. (2000) did not find a significant difference from an economic viewpoint between soil and foliar B applications but found that B applied by both methods was beneficial to cotton. No research on different rates or method of application of B for root chicory have been cited in the literature.

Since no literature reviews on B field experiments for root chicory could be found, a trial was conducted to determine the response of chicory to B application as both a soil amendment and as a foliar spray. In addition, soil B movement in the upper 60 cm of the soil was also studied. The hypotheses for the study were that (i) there is no difference in crop response

between the application methods, (ii) chicory will grow and thrive at applications of 3.5 kg B ha⁻¹ and (iii) B movement in the soil is significant at p<0.05.

5.2 Materials and methods

5.2.1 Site

The trial was conducted at the Dundee Agricultural Research Station (DARS), KwaZulu-Natal (KZN), South Africa (Chapter 3, Figure 3.1). The site description is the same as that given in Section 3.2.1. The coordinates for the site are 28.137556 S; 30.313417 E; 1 216 m. a.s.l.

5.2.2 Trial design

A 2 x 8 Latin square design was used, with four replications (64 plots in total). Eight rates of B (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 kg ha⁻¹) as disodium octaborate tetrahydrate (Na₂B₈O₁₃.4H₂O; 20.5% B) using Solubor®, and two methods of B application (soil-applied and foliar-applied) were used. The nomenclature used to describe the fertiliser application and treatments will subsequently be referred to as B0, B0.5, B1.0, B1.5, B2.0, B2.5, B3.0 and B3.5 with soil application and foliar application.

The trial, carried out during 2013 and 2014, was planted to the cultivar *Orchies* in autumn (1st April) and harvested 260 days after sowing (DAS) on the 17th December in both years. Allowance for the coldest period (15th June to 30th July) was given to let the crop respond; hence the late harvesting date. A gross plot size of 4x5 m with a nett plot size of 3 x 4 m was used. A row spacing of 50 cm was planted with an inter-row spacing of 8 cm, achieved at 35-40 DAS. The number of plants per gross plot was approximately 525, with 250 to 300 per harvested nett plot. The same hand planter and procedure was used as described in Chapter 3 (Section 3.2.2.1).

Dolomitic lime was applied by hand 8 weeks prior to planting at 1.5 t ha⁻¹, to decrease acid saturation percentage and increase calcium (Ca) and magnesium (Mg) levels as determined from the average exchangeable acidity and total cations according to Manson et al. (2012). This lime type was chosen due to the inherent shortage of Mg and Ca in the soil. For the soil application, the given rates were achieved by dissolving the equivalent amount of Solubor® in 10 L water and applying evenly per plot. It was soil incorporated during seedbed

preparation. The foliar application was split and applied three times during the growth of the crop at 60, 90, and 120 DAS. Aqueous solutions were prepared by dissolving appropriate amounts of Solubor® in 1 L of deionized water. A surfactant (0.05% w/v) was used for all foliar applications. The 1 L of solution was evenly sprayed over the six rows in each 5 m plot, which left the leaves wet, but not dripping. The solution had a range of pH from 4.0 to 4.3.

The trial site was known to be low in B, Ca, potassium (K), Mg, nitrogen (N) and sulphur (S). The trial was therefore fertilised with 90 kg N ha⁻¹ as ammonium sulphate (21% N, 24 % S), single superphosphate (10.5% P, 13% S) at 30 kg P ha⁻¹ and K at the rate of 150 kg ha⁻¹ as potassium chloride (KCl) (52% K) to avoid suppression of Ca uptake by high K (Hadas and Hagin, 1972). The initial lower fertilisation with N and K was done so as to avoid any possible interferences on the availability of B (Chapman and Vanselow, 1955; Sinha, 1961; Patel, 1967; Hadas and Hagin, 1972; Gupta et al., 1973). The fertilisers were spread by hand prior to planting and incorporated with a Kongskilde Vibroflex® (Kongskilde SA (Pty) Ltd) multi-tine cultivator.

5.2.3 Experimental procedure

5.2.3.1 Soil

The soil, classified and sampled after digging a soil profile pit representative of the trial area, was an Avalon 1100, Blackmoor family (Soil Classification Working Group, 1991); Typic Plinthaquult (Soil Survey Staff, 2014), similar to that described in Chapter 3 (Appendix 3.2).

5.2.3.2 Land preparation

The same method of land preparation was used as reported in Chapter 3 (Section 3.2.2.1).

5.2.3.3 Weed, nematode control and irrigation

Balan® was used as a pre-emergence herbicide. Due to low weed pressure only hand hoeing was necessary at 46 DAS. Once the crop had a complete canopy (90 DAS), further weed control was unnecessary.

The irrigation was similar for the germination period as previously described (Section 3.2.2.2), but changed due to a lower water requirement during late autumn and winter, done

according to soil tensiometer readings and it amounted to approximately 15 mm week⁻¹. For both years at the start of warmer weather (about the middle of August) weekly amounts were increased to 30 mm, pending rainfall. The water supply source was as previously reported (Section 3.2.2.2; Appendix 3.3).

5.2.3.4 Soil sampling and analysis

The same sampling technique and analytical procedures were followed as described for the NxPxL trial (Chapter 3). The analysis of B was carried out using the hot water soluble extraction method (hwsB) following a slightly modified analytical procedure to that described by Berger and Troug (1939). The procedure is given in Appendix 5.1. Initial soil sampling with a core sampler was carried out in 2012 at 0-15, 15-30, 30-45 and 45-60 cm (Table 5.1).

5.2.3.5 Leaf sampling and analysis

Leaf sampling was done on all plants twice during the growth of the crop. The first sample was collected at 60 DAS, immediately before the first foliar application of B, and the second immediately prior to harvesting. The analytical procedure for the leaf samples was the same as previously described (Section 3.2.3.2; Appendix 3.5).

5.2.3.6 Root sampling and analysis

Root sampling and analysis was done for the 2014 harvest only, according to the methods previously described (Section 3.2.3.3; Appendix 3.5).

5.2.3.7 Harvest

The harvest procedure was the same as described in Section 3.2.3.4. All leaf material was incorporated into the respective trial plots after the 2013 harvest.

5.1.3.8 Statistical analysis

The same procedure as given in Section 3.2.3.5 was used.

5.3 Results and discussion

The results are presented as means for the harvest periods (2013 and 2014) for yield, leaf analysis and soil analysis. Root analysis is reported for the 2014 harvest only.

5.3.1 Root yield and quality

Yield was not significantly correlated in either year with B application rate, application method (App) or App x B applied (Appendix 5.2).

Yields were lower than those of the N x P x L and N x K trials (Chapters 3 and 4, respectively) due to the lower fertiliser application rates. Gupta et al. (1985) suggested that, except for very deficient cases, a response to B is not as intense as with other micronutrients. Bell et al. (1989) also found a lack of B deficiency symptoms on three potted sandy soils deficient in B planted to Black Gram (*Vigna mungo* (L.) Hepper). Nyborg and Hoyt (1970), Gupta et al. (1985) and Schon and Blevins (1990) noted that the response of plants to added B seemed inconsistent. Schon and Blevins (1990) ascribed this to the narrow range of tolerance between B deficiency and toxicity that makes assessing B fertilisation requirements problematic. Gupta et al. (1985) suggested that soil-applied B was easily bound by organic matter as well as by iron and aluminium hydroxides making it unavailable for uptake by plants. Furthermore, B is relatively immobile in the plant (Gupta and Cutcliffe, 1985) so that redistribution to developing parts is minimal.

The root length of chicory showed a significant difference between B treatment levels as a quadratic function ($p=0.014$) in 2013. However, in 2014 this was not significant ($p=0.121$). The greatest root length occurred with B1.5-B2.0 application levels before decreasing with higher applied B. From field observation the plants from the control plots showed a slight greying to blackening of the root approximately 1 cm from the crown (Plate 5.1) that is probably indicative of a B deficiency (Shorrocks, 1997). At the higher B application rates there was no apparent visual damage to explain the root length decrease and, since the trial was irrigated, there was no water stress. Dugger (1983) and Broadley et al. (2012) noted that B deficiency inhibited root elongation, while Dell and Huang (1997) determined that root growth was more sensitive to B deficiency than shoot growth.



Plate 5.1: Greying in colour of cross sections of the root crown area symptomatic of boron deficiency from control plots.

Although the root length measurements did not show any conclusive evidence related to B deficiency, multiple rooting in the plants from the control plots was significantly higher than from the plots that received increasing amounts of B (Figure 5.1). From an industrial processing point of view, a large number of small roots are not favoured for the initial cubing process before roasting, and result in a large proportion of fines (R. Mahlangu, Chicory Processing Plant Manager, Umbambano Cooperative, pers.comm. 2015). Boron deficiency causes a loss of cell wall plasticity (Hu and Brown, 1994) and it is possible that low B resulted in abnormal cell wall formation and different physical properties (Fleischer et al., 1999; Ryden et al., 2003). The resultant deformation could also result in abnormality if the shape and size of the newly divided cells result in multiple roots. In boron-deficient plants, when the primary root tip prematurely ceases to grow, many lateral root tips start to grow out behind the primary root tip (Dell and Huang, 1997). Plate 5.2 illustrates this result of a possible boron deficiency.

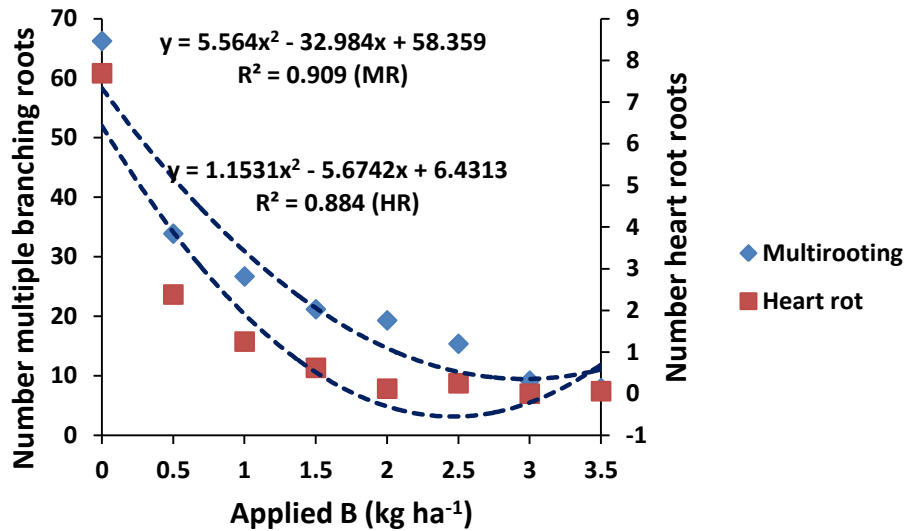


Figure 5.1: Mean number (n=8) number of multiple branching roots (MR) and heart rot (HR) with applied boron (B) treatments for the 2013 and 2014 harvests for both methods of application (Heart rot: CV% 81.1, l.s.d. 2.232, S.E.M. 1.254; Multiple branching roots: CV% 17.2, l.s.d. 7.624, S.E.M. 4.291 all at $p < 0.05$).



Plate 5.2: Examples of multiple rooting of chicory from control plots.

The number of plants affected by heart rot in the control plots was significantly higher ($p < 0.05$) than in the plots treated with B (Figure 5.1). It is therefore clear that B had an effect

in this trial, but it is recognised that it may not occur at different N or Ca levels or nematode pressure (Bartz et al., 1979; Canaday and Wyatt, 1992; Carballo et al., 1994). Nitrogen fertilisation interacts with the production of plant defence substances such as phenols and inhibits Ca uptake (Reerink, 1992). Schober and Vermeulen (1999) surmised that a lack of Ca played an important role in soft rot formation in witloof chicory based on research on potatoes (*Solanum tuberosum* L.) by McGuire and Kelman (1986). In addition, the influence of nematodes as a precursor for secondary infection should not be ruled out (Prinsloo, 1986). The root-knot nematode (*Meloidogyne spp.*) was noted as being present but not significantly (<2% from a randomly selected sample of 100 border row roots) on the trial site.

5.3.2 Soil analysis

The initial analytical soil data are given in Table 5.1 and as in Chapters 3 and 4 show that the soil was a loamy sand that increased in clay with depth with high medium and fine sand fractions. The soil was low in Ca, Mg, K and B.

Table 5.1: Some soil physical and chemical properties of the 0-15, 15-30, 30-45 and 45-60 cm depths of the soil at the trial site prior to cultivation

Parameter	0-15 (cm)	15-30 (cm)	30-45 (cm)	45-60 (cm)
Clay (%)	8.3	10.9	18.4	27.3
Coarse silt (%)	8.3	8.0	7.7	7.4
Fine silt (%)	3.5	3.8	3.9	4.9
Coarse sand (%)	14.5	13.6	12.5	11.8
Medium sand (%)	23.9	22.6	17.9	16.3
Fine sand (%)	27.0	26.7	25.7	18.5
Very fine sand (%)	14.5	14.4	13.9	13.8
Sample density (g mL ⁻¹)	1.34	1.32	1.30	1.28
pH(KCl)	4.27	4.21	4.25	4.84
Acid saturation (%)	20	18	9	3
Cation exchange capacity (cmol L ⁻¹)	2.62	2.87	3.20	3.57
Exchangeable Ca (mg L ⁻¹)	293	290	302	345
Exchangeable Mg (mg L ⁻¹)	66	75	78	208
Exchangeable K (mg L ⁻¹)	80	72	63	47
Extractable P (mg L ⁻¹)	36	2	3	2
Extractable B (mg kg ⁻¹)	0.03	0.02	0.01	0.01

5.3.2.1 Boron at 0-15 cm depth

The initial soil B prior to cultivation ranged from 0.02 to 0.03 mg kg⁻¹ as sampled from each plot, which is very low according to Fleming (1980) and Shorrocks (1997). The soil at the trial site falls into Category I according to Fleming (1980) (Table 5.2).

Table 5.2: General guideline categories for hot water soluble boron (B) in soils (Fleming, 1980)

Category	Hot water soluble B ($\mu\text{g mL}^{-1}$)	Description
I	< 1	Normal plant growth suffers due to insufficient water-soluble boron.
II	1 - 5	Normal plant growth: sufficient water-soluble boron.
III	>5	Possible toxic quantities for plants

Harvest 2013

After the first harvest the soil B ranged from 0.09 to 0.26 mg kg⁻¹, increasing with increase in applied B. The foliar application resulted in higher B accumulation in the 0-15 cm depth than the soil application. This was possibly the result of wash from the foliar spray application. The amount of B in the 0-15 cm depth was highly significantly correlated ($p < 0.001$) with the application method ($p < 0.001$), the B treatment level ($p < 0.001$), and their interaction ($p < 0.001$) (Appendix 5.3).

Harvest 2014

After the second harvest, the B in the 0-15 cm depth ranged from 0.11 to 0.28 mg kg⁻¹. This small increase over the 2013 results is possibly due to a slight residual effect from the earlier harvest. The accumulation of B in the 0-15 cm depth typically showed a positive trend with applied B.

However, in contrast to 2013, the soil application resulted in higher B than that of the foliar application. In all likelihood the residual soil B from 2013 plus the added B from 2014 resulted in the higher B values. In contrast, the foliar-applied B could have been better adsorbed than in 2013 with minimal wash into the soil. The amount of B in the 0-15 cm depth was highly significantly correlated with the application method ($p < 0.001$), and B treatment

level ($p < 0.001$), but was not significant with respect to their interaction (Refer to Appendix 5.3).

Average of the two years

The mean soil B in the 0-15 cm depth, for the two years combined, ranged from 0.10 to 0.27 mg kg^{-1} plot⁻¹. Over the trial duration, time and time x method of application were also highly significant ($p < 0.001$), along with time x B applied x method of application. The grand mean for the two years was 0.19 mg B kg^{-1} for the combination of the two methods of application across all the treatment levels of B. For the individual years of 2013 and 2014 this was 0.17 and 0.21 mg B kg^{-1} , respectively.

The result of B applied with the two methods of application for the two time periods shows a positive trend with the foliar application resulting in higher B in the 0-15 cm depth (Figure 5.2). The slight difference between the application methods could have resulted from foliar wash onto the soil surface that was incorporated later over a period of time, compared to the earlier soil-applied B that had more time to leach into the soil.

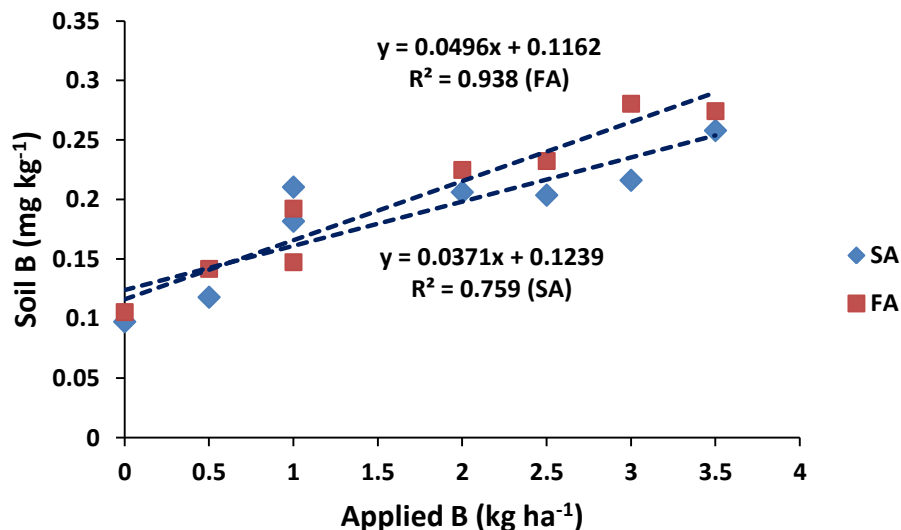


Figure 5.2: Mean ($n=8$) hot water soluble boron (B) at harvest in the 0-15 cm soil depth for soil-applied (SA) and foliar-applied (FA) B with different amounts of applied B (CV% 22.9, l.s.d. 0.07067, S.E.M. 0.0417 at $p < 0.05$).

Initial (2012) and final (2014) 0-15 cm depth boron comparison

Many researchers working on the effect of the rate of B application (Sinha et al., 1991; Mortvedt and Woodruff, 1993; Asad et al., 2003; Dordas, 2006; Brighenti and Castro, 2008)

have found, depending on crop type and the application method, 0.25 to 3.0 kg B ha⁻¹ to be adequate for most crops. Root chicory did not show any negative effects to the application of 3.5 kg B ha⁻¹ either soil-applied or as a split-applied foliar application.

On a hwsB basis it seems that many crops have a critical concentration for B which ranges from 0.15 to 0.50 mg B kg⁻¹ soil (Gupta and Cutcliffe, 1973; Morrill et al., 1977; Howeler et al., 1978; Li et al., 1978; Aitken et al., 1987; Sakal et al., 1988; Bell, 1997). After two seasons of B treatment, the soil hwsB at 0-15 cm depth ranged from 0.10 to 0.27 mg kg⁻¹ which would still be regarded as deficient for some crops. On the B3.5 plots at the end of 2014 soil-applied hwsB averaged 0.34 mg B kg⁻¹ while the foliar-applied B averaged 0.29 mg B kg⁻¹ in the 0-15 cm depth.

5.3.2.2 Boron in the 15-30 and 30-45 cm depths

The B in these depth ranges was not significantly different to the 0-15 cm depth and therefore no further discussion is presented.

5.3.2.3 Boron in the 45-60 cm depth

Harvest 2013

The difference between the 0-15 cm and the 45-60 cm depths for the 2013 harvest was highly significant ($p < 0.01$) for the B application rate, the method of application, and their interaction. There was a positive increase in B from the different B application rates while the foliar application was significantly different to the soil application.

Harvest 2014

The difference between the 0-15 cm depth and 45-60 cm depth for the 2014 harvest was moderately significant ($p = 0.036$). The method of application was still significant but less so than for 2013 ($p = 0.008$). The interaction of B x App was, however, not significant ($p = 0.380$). Boron continued to increase positively as in 2013 to B2.5 and then decreased slightly. In contrast to 2013, the soil application showed higher B in the subsoil.

Average of soil sampled after two harvests

The difference between topsoil and subsoil (45-60 cm) B after each harvest was highly significant ($p < 0.001$). However, method of application and B x App were not significant.

Time x B was moderately significant ($p=0.077$) with T x App highly significant ($p<0.001$) and the combination time x B x App significant ($p=0.019$). Overall there was a positive difference between topsoil and subsoil with increasing B application over both application methods.

Initial (2012) and final (2014) 45-60 cm depth boron comparison

The analysis of variance showed that the difference between the initial and final B at 45-60 cm depth was significant at $p<0.05$ and was also highly significant for time and time x B applied ($p<0.001$) (Figure 5.3).

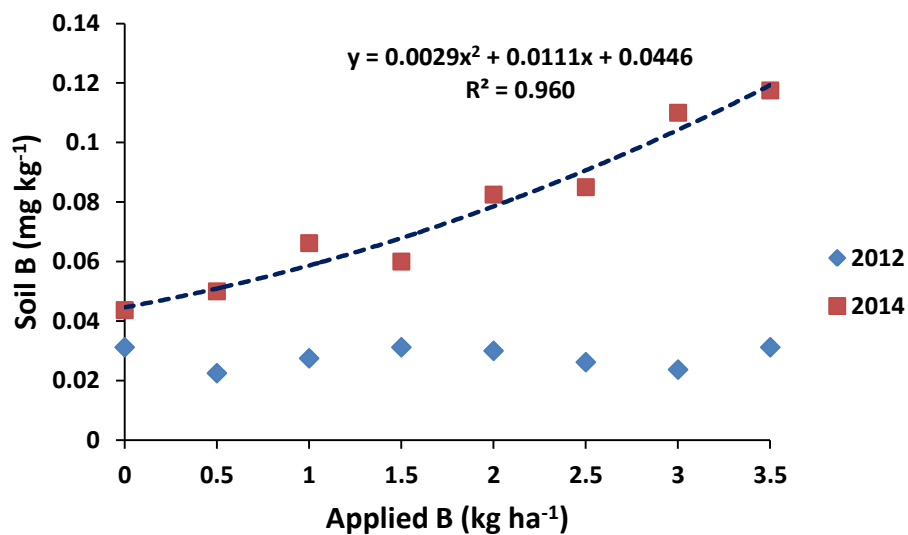


Figure 5.3: Mean initial (2012) (n=4) and final (2014) (n=8) hot water soluble boron (B) at 45-60 cm soil depth with different amounts of applied B over all applications for two seasons (Final 2014: CV% 46.9, l.s.d. 0.02658, S.E.M. 0.02461 at $p<0.05$).

The increase in B in the 45-60 cm depth supports the findings of numerous researchers that have found B to be highly mobile, especially in sandy soils (Eaton, 1935; Berger and Truog, 1940; Wear and Patterson, 1962; Bingham, 1973; Gupta, 1980; Keren et al., 1985; Goldberg et al. et al., 1993; Shorrocks, 1997; Yan et al., 2006).

Subsoil values (45-60 cm) ranged from 0.01 to 0.04 mg B kg⁻¹ initially and 0.02 to 0.21 mg B kg⁻¹ after two years over the trial as a whole. The maximum B concentration in the subsoil represents a large increase over the initial subsoil B with the initial figure only equivalent to between 4.7 and 19% of the final subsoil B. This strongly suggests that B has moved down the profile during the course of the trial. This residual amount in the subsoil, while significant

under the trial conditions, will be insufficient to have any negative effect on subsequent crops from a B toxicity perspective.

The movement of B in soil is largely dependent on its texture, pH, moisture content and soil temperature. The texture of the sand fraction of the soil at the trial site showed an increase in the coarse sand fraction with depth and this is likely to allow easy B movement. Sandy soils with finer-textured subsoils generally do not respond as much to the addition of B as do those with coarser-textured subsoils (Wear and Patterson, 1962; Fleming, 1980). The removal of added B depends also on the quantity and frequency of water added (Tanji, 1970; Wild and Mazaheri, 1979).

The pH(KCl) at the start of the trial showed an increasing pH with depth. The values were, however, still sufficiently acidic to encourage the downward movement of B. When pH is below 7, B occurs in its undissociated form $B(OH)_3 + H_2O$ and is absorbed by plant roots in this form (Hu and Brown 1997; Power and Woods, 1997). Boron is not fixed under these conditions and easily leaches (Gupta, 1980, Keren et al., 1985; Goldberg et al., 1993; Shorrocks, 1997; Yan et al., 2006).

At the start of the trial the soil organic carbon was measured as it has been reported by numerous researchers that the organic fraction plays a vital role in the retention of available soil B (Hara and Tamai, 1968; Elrashidi and O'Connor 1982; Evans, 1987; Shorrocks, 1997). When this organic matter starts to decompose the B is released and a portion is taken up by plants while the rest is lost by leaching. The average organic carbon of the topsoil at initiation of the trial was 0.96% and it was 1.05% at trial completion. These organic carbon values are not significantly different from each other and so it would not have contributed significantly to altering background B levels. In the subsoil the organic carbon was <0.05% and so too low to play any significant role in B adsorption or desorption (Elrashidi and O'Connor, 1982; Goldberg, 1997; Chaudhary et al., 2005).

Moisture and temperature also play an important role as B availability decreases with less moisture. However, under the irrigated trial conditions this was unlikely to be a problem. The trial site therefore was an ideal environment for low initial soil B and, with irrigation, was conducive to B leaching.

In soils of arid and semi-arid or warm humid areas, B accumulates in the surface horizon. However, in cooler humid climates, soil B is leached. At the DARS trial site which is situated in a warm temperate area of South Africa on a loamy sand, with an average rainfall of 743 mm yr⁻¹, a high degree of leaching is prevalent especially from the topsoil and is reflected in the low soil B results.

5.3.3 Leaf analysis

At 60 DAS leaf B was significantly correlated ($p=0.003$) (Appendix 5.4) with the added B application rates for the two harvests (Figure 5.4). At harvest, leaf B was highly significantly correlated with B applied and App ($p<0.001$) and moderately with time x App ($p=0.052$). The leaf B at harvest was higher than at 60 DAS due to the manner in which B is stored in the plant. The distribution of B in the plant has been ascribed to its high mobility in the xylem and limited mobility in the phloem and, as a result, B accumulates in older tissue and in the leaf tips and margins (Bowen 1968, 1969; Oertli and Roth, 1969; Reisenauer et al., 1973; Bowen and Nissen, 1977; Shorrocks, 1997). Retranslocation from the old leaves to new tissue via the phloem is negligible (Wolf, 1940; Eaton, 1944; Dible and Berger, 1952; Oertli and Roth, 1969; Shorrocks, 1997). However, there is evidence that this is crop species dependent (Brown and Shelp, 1997).

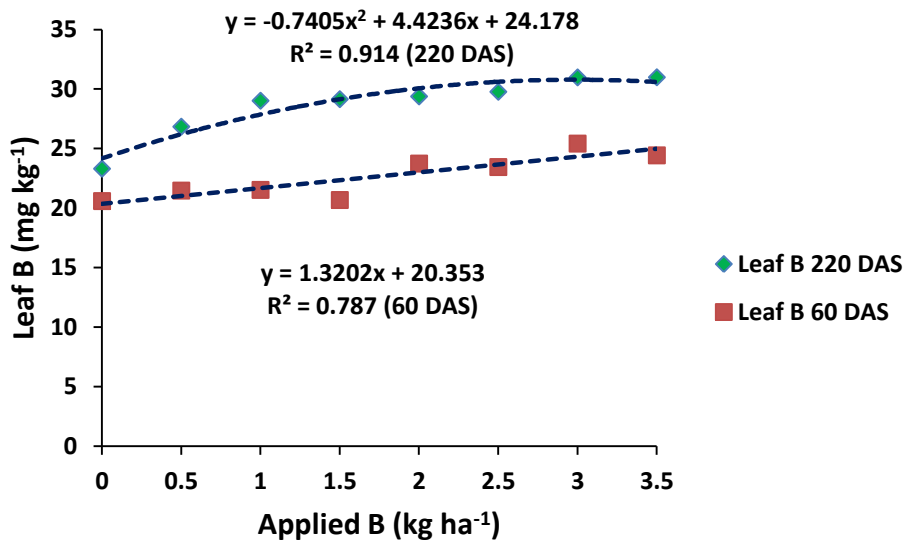


Figure 5.4: Comparison of mean leaf boron (B) at 60 and 220 days after sowing (DAS) over all applications, with different amounts of applied B for two seasons (n=8) (Leaf B at (a) 60 DAS: CV% 8.5, l.s.d. 4.2728, S.E.M. 1.931; and (b) 220 DAS: CV% 12.7, l.s.d. 5.424, S.E.M. 3.634 at $p<0.05$).

The 60 DAS leaf sampling had, on average, B that ranged from 20.49 to 25.42 mg kg⁻¹ over the different B application rates. These values would be regarded as low but not necessarily deficient (Eaton, 1944; Gupta, 1980; Gupta et al., 1985; Shorrocks, 1997). From personal field observations on leaf growth this seems to be confirmed as only a few plants within the control plots showed what could have been a B-induced P deficiency (Plate 5.3). Boron deficiency symptoms are first visible in the death of growing tips. The leaves are usually thick, have a coppery texture, and become curled and brittle. Other symptoms include stunted roots with internal tissue disintegration, causing abnormalities such as distorted or secondary root formation (Goldbach, 1997; Brown et al., 2002; Broadley et al., 2012). Heart rot is common in the crown area of deficient roots (Van Hee and Bockstaele, 1983). The plants did not show these classic signs of a severe B deficiency.



Plate 5.3: Purple veining, possibly a result of a boron-induced phosphorus deficiency, in chicory leaves from the control plots.

In general, for most plant species, field deficiencies of B occur in plants sensitive to B when there is less than 15 mg B kg⁻¹ (on a dry matter basis), while it seems that a B concentration of 20-100 mg B kg⁻¹ is adequate for growth (Gupta et al., 1985). Nelson et al. (1964) have reported that legumes such as alfalfa (*Medicago sativa* L.) have sufficient B when concentrations are above 35 mg B kg⁻¹. On the other hand, Stinson (1953) reported that alfalfa became deficient when it contained less than 20 mg B kg⁻¹. In red clover (*Trifolium*

pratense L.) Gupta (1984) reported that less than 20 mg B kg⁻¹ resulted in evidence of deficiency, while in alfalfa less than 30 mg B kg⁻¹ was the concentration at which it showed deficiency symptoms. Such divergent B results reflect the data obtained on different soil types under different environments (Warington, 1933; Parr and Loughman, 1983; Noppakoonwong et al., 1993; Cakmak et al., 1995) and highlights the importance of considering environmental factors when reporting on B.

Cognisance needs to be taken that there is also an interrelationship between B and N, P, K and Ca in plants (Chapman and Vanselow, 1955; Fox 1968; Cutcliffe and Gupta, 1980; US Borax, 2009). Its interaction (synergistic or antagonistic) with many plant nutrients may be influential in regulating soil B availability to plants.

Shorrocks (1997) for sugar beet (*Beta vulgaris* L.) (a comparable crop to root chicory) suggested a five class rating for amounts of leaf B (Table 5.3). The results from the present field trial suggest that the lowest three categories reflect what has been found.

Table 5.3: Leaf boron (B) classification for sugar beet as proposed by Shorrocks (1997)

Leaf B range (mg kg ⁻¹)	Rating
< 20	deficient
20-25	low
25-50	normal
50	high
>300	excess

There have been other approaches to determine the deficiency and toxicity levels of B. Use has been made of the chemical ratios in plant tissue (Marsh and Shive, 1941; Jones and Scarseth, 1944; Tanaka, 1967; Gupta and Cutcliffe, 1972) and these researchers suggested that the tissue Ca : B ratio may be a good index for detecting B deficiency and toxicity in plants. These ratios are plant specific and no ratios for chicory were given. Analysis of the 60 DAS leaf sampling gave a Ca : B ratio range of 213 to 466, with the former occurring in leaves in the 25-50 mg kg⁻¹ ‘normal’ class of Shorrocks (1997) (Table 5.3) and the latter in the ‘low’ <20 mg kg⁻¹ class. Gupta (1972) found that Ca : B ratios of 10-45 were toxic to barley (*Hordeum vulgare* L.), while a ratio of 180 was regarded as optimal; a ratio of 697 showed up as a B deficiency. Chauhan and Asthana (1981) found tissue Ca : B ratios were

almost constant and independent of the sampling time when toxicity symptoms occurred in lentils (*Lens culinaris* L.), barley and oats (*Avena sativa* L.). However, Gupta (1980) found that the results for diagnosis based on this ratio were inconclusive.

Solubor® is usually recommended at 0.2-0.5 w/v concentration for a split foliar application during the early growth period of the crop (Shorrocks, 1997). For the trial, foliar application phytotoxicity was not problematic at the highest rate of 3.5 kg B ha⁻¹ (split into three applications) and no evidence of leaf damage was found. Phytotoxicity according to Martens and Westermann (1991) could be a problem at the higher rates of application, as experienced by Asad et al. (2003) and Brighenti and Castro (2008) working with total B foliar application rates of 1.3 kg B ha⁻¹ and 0.5 to 0.7 kg B ha⁻¹ on sunflowers (*Helianthus annuus* L.) in Australia and Brazil, respectively, and highlights the sensitivity of sunflowers to B foliar application rates, compared to root chicory.

The B leaf analysis of the chicory at the different sampling times (60 DAS and at harvest) showed a significant difference in B accumulation, with higher B occurring at harvest. Working on sugar beet (*Beta vulgaris* L.), Vlamis and Ulrich (1971) found similar results with the highest values of B occurring in the older leaves, while the lowest B content occurred in the fibrous and storage roots. Other researchers (McClung and Lott, 1956; Bradford and Harding, 1957; Labanauskas et al., 1959; Mukherjee, 1969) also found that B uptake varies with the growth stage of the plant. However, other crop types showed the opposite as Gupta and Cutcliffe (1973) reported that B levels in leaf tissue of cole crops were generally lower later in the growing season than they were in the early season. Similar results were obtained with rutabaga (*Brassica napobrassica* L.), where the B content of leaf tissue was greater from early samplings than it was from late samplings (Gupta and Cutcliffe, 1971).

Since root chicory is harvested before flower and seed set, B requirements might be different depending on the age of the plant and if seed collection was a primary objective. It is possible that different stages of reproductive growth are sensitive to B deficiency (Bell, 1997). For the prognosis of B deficiency in leaves of sugar beet in the USA, Vlamis and Ulrich (1971) suggested 15-30 mg B kg⁻¹ in the leaf to be the critical B range at which a 10% yield reduction could be expected using oven dried mature leaves. Their breakpoint occurred at 21 mg B kg⁻¹. In a number of dicotyledons, leaf B concentrations of <10 mg B kg⁻¹ dry weight were generally associated with deficiency symptoms in the sampled leaves (Bell, 1997).

Goldbach, (1997), Brown et al. (2002) and Broadley et al. (2012) have described B deficiency symptoms for a variety of plants (chicory excluded) of which the control plots at a leaf B level of 20.5 mg B kg⁻¹ (at 60 DAS) did not show the classic signs as described earlier and this suggests that the critical leaf B is <20.5 mg B kg⁻¹. In addition, there is a variation in concentration between the plant parts, of which leaves accumulate the most (Miller and Smith, 1977; Brown and Shelp, 1997). Wolf (1940) found that in low B soils most of the B was in the stem of a variety of plants. Hodgkiss et al. (1942) working with soybean (*Glycine max* L. Merr.) established that the leaves contained the highest concentration of B (52-100 mg B kg⁻¹), followed by the growing tip (28-59 mg B kg⁻¹) and that the stems contained the least. However, it has also been shown by Sayre (1958), Kohl and Oertli (1961) and Shorrocks (1974) that even within the plant parts the distribution of B can vary and that it has, for example, a tendency to accumulate in the leaf margins.

At harvest there was a highly significant difference between leaf B concentration and applied B ($p < 0.001$) and the method of application ($p < 0.001$) (Figure 5.5). The time x App was moderately significant ($p = 0.052$).

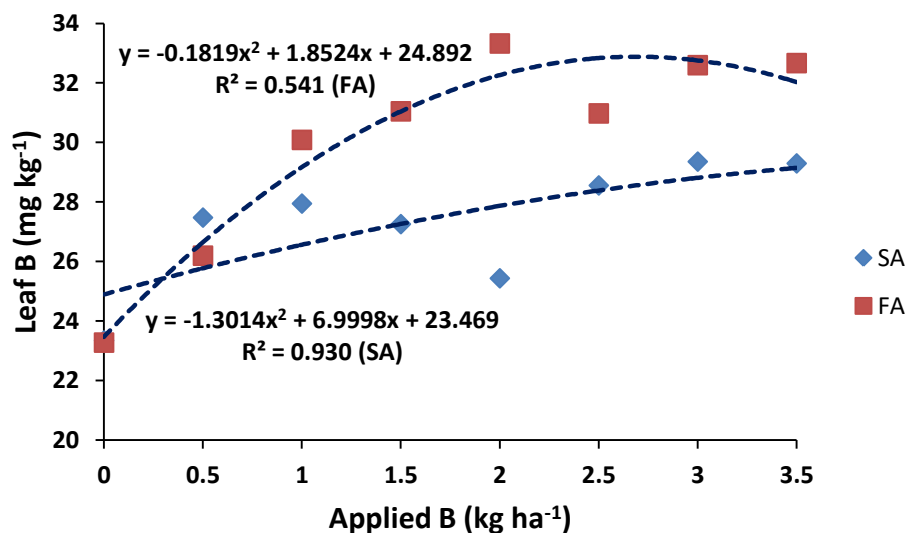


Figure 5.5: Mean (n=8) leaf boron (B) at harvest for soil-applied (SA) and foliar-applied (FA) B with different amounts of applied B for two seasons (CV% 12.7, l.s.d. 5.424, S.E.M. 3.634 at $p < 0.05$).

The application of foliar-applied B seemed to be more effective than soil-applied B (Figure 5.5) on this low B soil and this supports work done by Gupta et al. (1985). In earlier work

Gupta and Cutcliffe (1978) working on rutabaga found that band-applied B (1.12 kg ha⁻¹) resulted in higher leaf B than when broadcast (2.24 kg ha⁻¹). Similarly, Peterson and MacGregor (1966) and Touchton and Boswell (1975) found the same phenomenon in maize. Additionally, Gupta and Cutcliffe (1978) established that higher amounts of B were needed to overcome B deficiency in rutabaga when broadcast than when foliar or band-applied. Work on soybean has shown that soil applications of B did not affect branching or the number of pods per branch as leaf B concentration did not change with B rate (Schon and Blevins, 1990).

The trial results for leaf B analysis seem to be more in keeping with field observation and support Woodruff (1979) that plant tissue analysis is a better indicator for evaluating B fertilisation requirements than soil analysis. The amount of B utilised by the leaves ranged from 103.7 to 131.4 g B ha⁻¹ for the soil application and 96.8 to 152.4 g B ha⁻¹ for the foliar application. The amount of B removed by the leaves is, however, an estimate as it is difficult to collect all of the leaf material from a field plot as some tend to die, drop off and blow away during the growing season. Despite this, the leaf B removed following foliar application was higher than after the soil application (Figure 5.6) probably due to its direct placement onto the crop and the lack of translocation to other parts of the plant. Although showing a progressive increase with B application rate the soil application was broadcast and the utilisation efficiency by the chicory crop was lower (Figure 5.6).

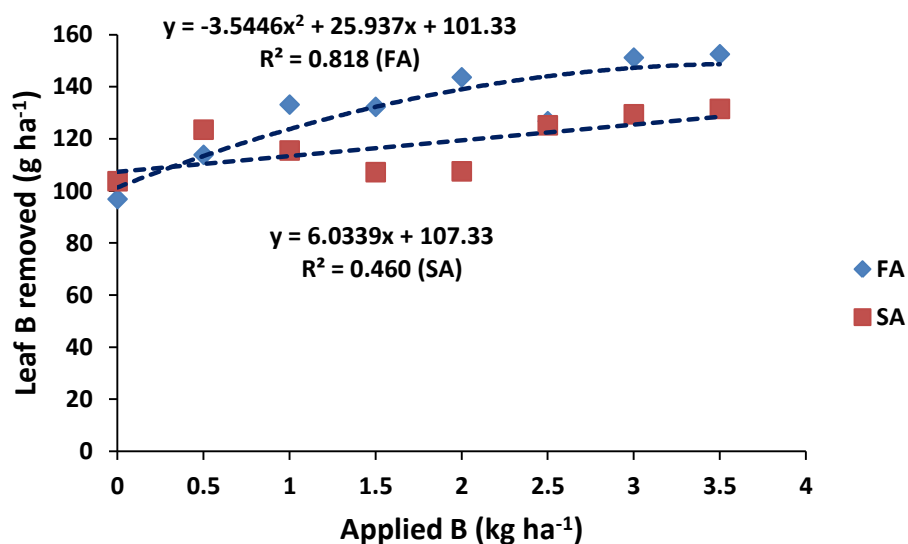


Figure 5.6: Mean (n=8) leaf boron (B) utilised for different application methods (FA=foliar-applied; SA=soil-applied) with different amounts of applied B.

5.3.4 Root analysis (2014)

The amount of B in the roots was significantly related to the amount of B applied ($p=0.039$) while the B applied \times App was moderately significant ($p=0.12$) (Appendix 5.5).

Across both application methods, there was a positive accumulation of B in the roots with increasing amounts of B applied. The concentration, however, was much smaller than that in the leaf (Figure 5.7). The leaf B concentration was more than 3.5 times greater than that in the root for the soil-applied treatment, while the foliar-applied treatment was only slightly less at 3.45 times. These findings confirm those of Miller and Smith (1977) and Brown and Shelp (1997) on the differences in B uptake by different plant parts. However, Bellaloui and Brown (1998) suggested that this phenomenon was cultivar and species specific from their greenhouse studies on celery (*Apium graveolens* L.), tomato (*Lycopersicon esculentum* L.) and wheat (*Triticum aestivum* L.).

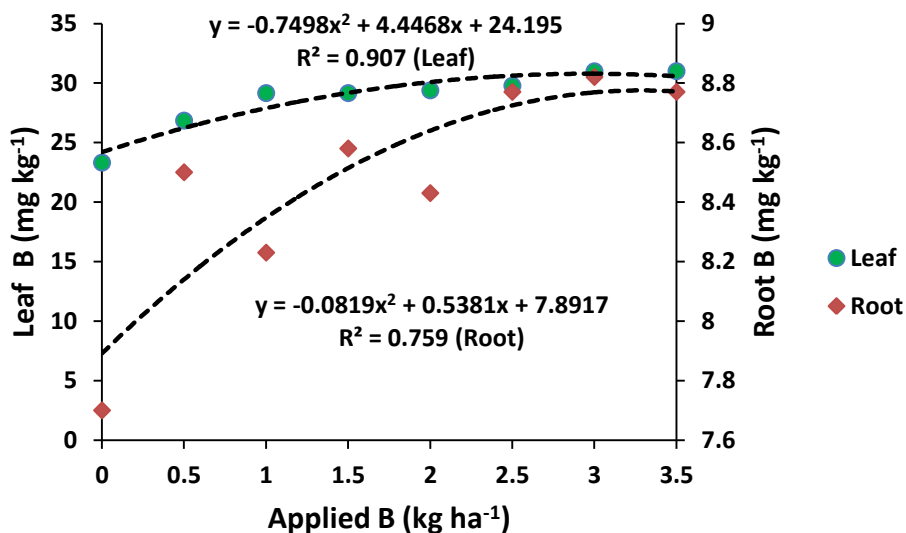


Figure 5.7: Leaf and root boron (B) at different B treatment levels over both soil and foliar application methods. Mean leaf data are for the second leaf sampling at 220 days after sowing over two seasons (n=8); root data are for 2014/2015 (n=4) (Leaf B: CV% 12.7, l.s.d. 5.424, S.E.M. 3.634; Root B: CV% 8.1, l.s.d. 0.9746, S.E.M. 0.6839 all at $p<0.05$).

The amount of B utilised by the roots ranged from 53.2 to 68.7 g B ha⁻¹ for the soil application and 57.3 to 68.1 g B ha⁻¹ for the foliar application (Figure 5.8). Soil-applied B uptake by the roots was higher than foliar-applied B, probably due to the length of time of exposure of the root to available B and the minimal translocation of B to the roots from the

foliar application. However, the differences between the two application methods were not significant at $p < 0.05$ due to the large standard error.

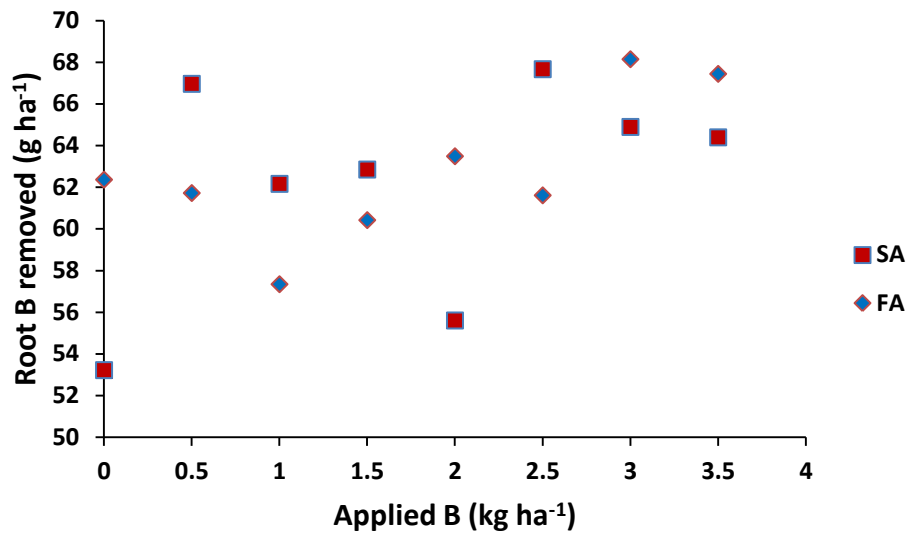


Figure 5.8: Removal of boron (B) by roots with different amounts of applied B for two application methods (SA: soil-applied; FA: foliar-applied) (n=8).

5.3.5 Soil boron extraction method

The relationship between leaf B and soil B over the two seasons is shown in Figure 5.9. The correlation increased substantially for the second leaf sampling at harvest due to the manner of B translocation in the plant over time, with maximum concentration found in the leaves. Offiah and Axley (1988) found that hwsB correlated well with plant uptake for soils previously treated with B fertiliser, but not for soils that had no history of B fertilisation. They surmised that possibly many of the B fixing sites needed to be filled before the hwsB correlation was improved. However, the amount of soil B extracted by the hwsB seemed extremely low in contrast to that extracted from the leaf. The soil extraction of B is reported to be extremely low, however, and the leaf B analysis suggests that the plant B level is in the sufficiency range. It therefore appears that root chicory's response to the B extracted by the hwsB method does not seem to reflect the plant response as in-field scouting did not indicate severe plant B shortages as would have been expected from the hwsB soil results. However, even on this low organic matter, sandy soil, with very low concentrations of hwsB, chicory was able to take up sufficient quantities of B to maximise dry-matter production. Although dry-matter production was maximised at zero applied B, preferential allocation to leaves seems to have resulted in sub-optimal B for high root quality.

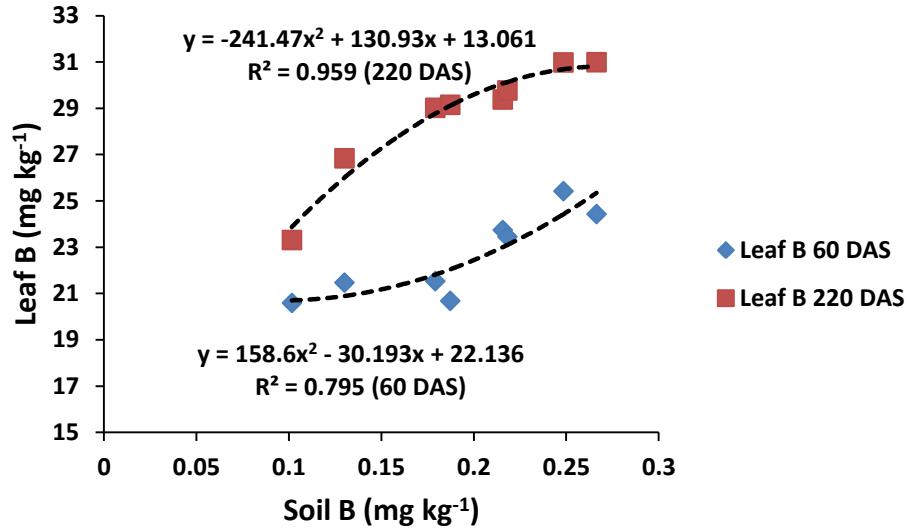


Figure 5.9: Relationship between leaf boron (B) at first (60 days after sowing (DAS)) and second sampling (220 DAS) and soil B (using the hot water soluble method of extraction) for two seasons (n=8) (Leaf B at (a) 60 DAS: CV% 8.5, l.s.d. 4.2728, S.E.M. 1.931; and (b) 220 DAS: CV% 12.7, l.s.d. 5.424, S.E.M. 3.634 at $p < 0.05$).

However, extraction with hot water is the most widely used method to estimate plant-available B (Berger and Truog, 1939; Deturk and Olson, 1941; Stinson, 1953; Miljkovic et al., 1966; Russell, 1973; Shorrocks, 1997). Reports suggest that when leaf B levels for many crops are in the range of 20 to 25 mg B kg⁻¹ (desired is 35 mg B kg⁻¹) on a dry-weight basis, additional B is needed (Fleming, 1980; Shorrocks, 1997) and this broadly concurs with the trial results. On a hot water extractable basis many crops have a critical concentration for B which ranges from 0.15 to 0.50 mg B kg⁻¹ soil. In the present trial chicory started to show slight visual signs of a B deficiency at 60 DAS with leaf boron of 20.5 mg B kg⁻¹ and soil B of 0.09 mg B kg⁻¹. The soil B at the termination of the trial peaked at 0.34 mg B kg⁻¹ for the soil-applied treatment (B3.5), a level still critical for many crops. Mahler and McDole (1981) found that cropped soils generally contain 0.3 to 1.5 mg kg⁻¹ of hwsB and that crops with a high requirement would require 0.5 mg B kg⁻¹. Gupta (1968) found that the hwsB ranged from 0.38 to 4.67 mg B kg⁻¹ in soils in eastern Canada. Bradford (1966), Gupta et al. (1985) and Sims and Johnson (1991) all give information on soil B levels that are both deficient and adequate for a selection of plants but excluding chicory.

Some researchers have found problems with the hwsB method in predicting crop response (e.g. Shiffler et al., 2005) and that there was no correlation under some management practices (Hamence and Oram, 1964; Gestring and Soltanpour, 1987; Offiah and Axley, 1988).

Russell (1973) and Goldberg et al. (1993) were of the opinion that plant-available B is soil specific and relates to the soil's physical and chemical properties, such as texture, clay mineralogy, pH and organic matter. Plants will generally take up more B from a more acid or coarser-textured soil for a given level of hwsB (Eaton, 1935; Wear and Patterson, 1962; Russell, 1973) than from a fine-textured, neutral or alkaline, higher clay soil. Due to soil variability, specific extraction techniques are often not suited to prediction of plant-available B (Parker and Gardner, 1981; Su et al., 1994). The important point is that it is the degree of correlation between the growth response and the quantity of B extracted (at B ranges that are deemed critical) that determines whether an extractant is suitable for differentiating potentially B-deficient from B-sufficient soils.

It is evident that although there are instances in which hwsB is highly correlated with plant uptake, it is not a definitive index of plant-available B in the soil (Deturk and Olson, 1941; Okazaki and Chao, 1968). This is probably a result of the way hot water extracts from the major three B pools (the organic, adsorbed inorganic and the soluble inorganic pools) (Gupta et al., 1985). Difficulty arises with the interplay between the three pools of B and their relationship to hwsB needs further study. However, there is a good correlation between hwsB and leaf B on the specific soil type at the present trial (Figure 5.9), and this study has shown that chicory root quality problems are likely at hwsB soil concentrations of less than 0.1 mg kg⁻¹.

5.4 Conclusion

5.4.1 Yield

Yield effects were not significant at the 5% level of significance for both seasons over all levels of B application. Application method and the App x B interaction were also not significant. Although the macronutrient fertiliser application was adequate for a response to added B, the chicory response was very limited. The relatively high level of 3.5 kg B ha⁻¹ applied did not have a negative effect on chicory performance under the prevailing field trial conditions.

5.4.2 Soil

In the 0-15 cm depth the combination of the two harvest periods indicated highly significant responses ($p<0.001$) of soil B to time, time x App, and B treatment level, while the interaction of time x App x B treatment level was significant at $p<0.05$.

Soil sampling at 45-60 cm showed a highly significant movement of B from the 0-15 cm depth. The treatment level, method of application and time were all significant ($p<0.05$) for the averaged data of the 0-15 and 45-60 cm depth comparison.

In the longer term, especially if slowly permeable clay is found at moderate depth and the soil is planted to a deep-rooted rotation crop sensitive to B, it could prove harmful. This emphasises the importance of correct crop rotation, B sensitivity and soil type selection.

5.4.3 Leaf

The combination of the 2013 and 2014 B leaf data for the sampling at 60 DAS showed a significant correlation with only the B treatment level, while the leaf B samples taken at harvest showed a highly significant interaction ($p<0.001$) between the App x B treatment level and a significant interaction ($p<0.05$) with time x App.

Foliar application split in three at the highest B treatment level of 3.5 kg B ha^{-1} did not show any leaf burn on the chicory leaves as can result with other crops (e.g. sunflower). Chicory seems to be tolerant of the relatively high application rates used in the trial.

The leaf B from the control plots was low, as was hwsB. Plants started to show minor B deficiency symptoms, but did not show the expected severe B shortage as implied by the hwsB results. The current research has shown that root chicory has a critical leaf B deficiency level of less than $20.5 \text{ mg B kg}^{-1}$ when considering root mass, but root quality was reduced at this level.

5.4.4 Roots

The root analysis done for 2014 only, showed that the amount of B in the root was moderately significantly correlated with added B at $p<0.05$. The interaction between the type of application and application rate effects on root B was also significant ($p=0.012$).

Cross sections of roots from the control plots showed that only a limited number had slight B deficiency symptoms. Root growth is more sensitive to B deficiency than shoot growth; therefore, the B levels attained in the roots were adequate for root chicory growth. However, it was observed that multiple rooting in plants especially in the control plots was significant when compared to those plots that received B and that the incidence of root rot was also slightly higher ($p < 0.05$) which might be due to a deficiency of B.

5.4.5 Soil boron extraction

The soil initially was very low in available B (0.09 mg kg^{-1}) in the 0-15 cm depth. After two seasons of B treatment the soil B ranged from 0.10 to $0.27 \text{ mg B kg}^{-1}$ in the 0-15 cm depth which would still be regarded as being below the critical concentration of B (0.5 mg kg^{-1}) for some crops. The hwsB, although sometimes highly correlated with plant B uptake, is not always a useful index of plant-available B in the soil. It seems as if the threshold hwsB required for optimal plant growth is soil specific and depends upon the individual soil's physical and chemical properties (Russell, 1973; Goldberg et al., 1993).

The hypotheses for the study i.e., that there is no difference in crop response between the application methods, that root chicory is tolerant to applications of 3.5 kg B ha^{-1} , and that B movement in the soil is appreciable can all be accepted from the trial results. Root quality (as indicated by forked roots and root rot) appears compromised at topsoil B concentrations of about 0.1 mg kg^{-1} .

CHAPTER SIX

INFLUENCE OF AMMONIUM SULPHATE AND DOLOMITIC LIME ON SOIL ACIDITY, AND LEAF AND ROOT INDICES OF ROOT CHICORY (*Cichorium intybus* var. *sativum*)

6.1 Introduction

Root chicory's origin is from south-western Europe and it was first found in the Lombardy region of Italy (Pearce, 1947). It has been suggested that it is best suited to deep, calcareous soil of medium texture (Gill et al., 1980).

International work on root chicory's soil-acidity preferences is sparse. There is mention in broad terms of pH values that are suitable (MAFF, 1988; Baert and van Bockstaele, 1993) but no definitive research has been carried out. The only investigation found which gives attention to this was that of Upjohn and Michalk (1999) who studied forage chicory in Australia. They used soil with a pH(CaCl₂) of 4.3, low phosphorus (11 mg kg⁻¹ Colwell P) and high aluminium saturation (41%) using different rates of lime in a pot experiment. It was established that a change in soil pH from 4.3 to 5.3 did not affect penetration of the chicory roots.

In South Africa root chicory is grown in soils with a variety of textures, although the main chicory-producing area of the Eastern Cape Province has sandy soils. In KwaZulu-Natal (KZN) soil textures are typically diverse from high to low clay. The acid saturation of the chicory lands in KZN varies greatly from zero to 60%. The performance of other crops in KZN (e.g. maize, soybean, potato) has been well documented with regard to the effects of acid saturation (Farina and Channon, 1991; Manson, 1997; Manson and Katusic, 2008) but this is lacking for root chicory.

The level of soil acidity that is tolerable in any situation is determined by the permissible acid saturation (PAS) of the crop to be grown. If soil acid saturation exceeds the PAS, excess acidity must be neutralised by liming (Manson et al., 2012). How chicory reacts to acidity is not yet adequately determined and thus the level of permissible acid saturation is unknown. The diverse values given in the literature stem, at least in part, from the different analytical

practices used for the measurement of pH. In addition, many laboratories do not report the acid saturation.

As root chicory is prone to soil-borne diseases (Woyts, 1928; Prinsloo, 1986; Baert and van Bockstaele, 1993), crop rotation is always advocated. However, while an indication of the susceptibility of other crops to acidity are known, the sensitivity of root chicory is unknown and so crop rotational planning is hampered. This information would therefore assist farmers who need to plan their soil management strategies.

Field data on changes of soil-acidity indices such as pH, calcium (Ca) and magnesium (Mg) saturation, base saturation (Ca+Mg+K+Na), and acid (H+Al) saturation with the application of ammonium sulphate are non-existent for root chicory under South African conditions. Ammonium sulphate contains about 21% nitrogen (N) as well as approximately 24% sulphur (S). It is known to cause soil acidity (Mulvaney et al., 1997; Bolan and Hedley, 2003; Fageria et al., 2010) and was chosen with this characteristic in mind.

The objective of this study was to determine the effect of different lime and N (ammonium sulphate source) application rates on the acid saturation of the soil used for the field trials reported in Chapters 3, 4 and 5. It was hypothesised that ammonium sulphate would acidify the soil sufficiently to have an effect on the yield of the root chicory crop grown under irrigation management.

6.2 Materials and Methods

6.2.1 Site

The trial was conducted on the Dundee Agricultural Research Station (DARS) in the KwaZulu-Natal Province, South Africa (Section 3.2.1; Figure 3.1) at 1 216 m.a.s.l. The coordinates for the site are 28.137333 S; 30.313639 E. *Eragrostis curvula* for hay production was planted for 30 years prior to the present trial being established. The application of a fertiliser mixture 1:0:1 (48) (24% N, 0% P, 24% potassium (K)) and limestone ammonium nitrate (28% N) over 30 years on a topsoil with a low clay percentage (9.4%), under dryland conditions, has resulted in a topsoil (0-30 cm) with a high acid saturation due to leaching of Ca, Mg, and K from the exchange complex.

6.2.2 Trial design

A 4x4 factorial design with four rates of N application (0, 60, 120 and 200 kg ha⁻¹) as ammonium sulphate (21% N) and four rates of dolomitic lime (0, 1, 3 and 7 t ha⁻¹) with three replications was used to position between some of the fertiliser treatments of the trials reported in (Chapters 3 and 4). The nomenclature used to describe the fertiliser application will subsequently be referred to as N0, N60, N120 and N200 for nitrogen; L0, L1, L3 and L7 for lime.

A gross plot size of 4 x 5 m with a nett plot size of 3 x 4 m planted with a row spacing of 50 cm and an inter-row spacing of 8 cm was used. The 48 experimental plots were planted on the 29th October and harvested on the 10th June for each planting, over the period 2013/14 to 2014/15 with two seasons of data, referred to as 2014 and 2015, being evaluated.

Potassium as potassium chloride (KCl (52)) was applied at the rate of 150 kg K ha⁻¹ across the trial, and P was applied at 30 kg ha⁻¹ using single superphosphate (10.5% P, 13% S). Boron (20.5% B) was applied at 2 kg ha⁻¹ as Solubor® as a soil treatment prior to planting. These fertiliser rates were based on previous trial results (Chapters 3, 4 and 5) that showed above-average yields on a similar soil type.

6.2.3 Experimental procedure

6.2.3.1 Soil

The experiment was conducted on an Avalon soil form, Blackmoor 1100 family (Soil Classification Working Group, 1991), Typic Plinthaquilt (Soil Survey Staff, 2014) similar to the soils in the previous trials (Chapters 3, 4, and 5) (Appendix 3.2).

6.2.3.2 Land preparation

The same method of land preparation was used as in the preceding trials (Section 3.2.2.1). The dolomitic lime was incorporated to 30 cm, eight weeks prior to planting, for the plots requiring lime treatment. Two thirds of the ammonium sulphate was incorporated to a 15 cm at planting, the balance was surface-applied 30 days after sowing (DAS).

6.2.3.3 Weed, nematode control and irrigation

The same weed and nematode control were used and the same irrigation scheduling procedure for spring planted chicory was followed as previously described (Section 3.2.2.2).

6.2.3.4 Soil sampling

Initial soil sampling was carried out in 2013 prior to cultivation. The trial layout was pegged out on the proposed area and each plot was sampled and analysed to different depths (0-15, 15-30, 30-45, 45-60, and 60-75 cm). Samples were grouped into their proposed lime and N treatment categories and mixed to get an average representative soil sample per treatment category. At the end of both seasons, soil sampling was carried out on each plot to a depth of 0-15 cm. After the second harvest in 2015, in addition to the 0-15 cm depth, soil samples were again taken at 15 cm intervals to 75 cm with a core sampler. The method of soil sampling per plot for the 0-15 cm depth and the analytical procedures used were as described for the N x P x L trial (Section 3.2.3.1).

6.2.3.5 Leaf sampling

The same leaf sampling and analytical procedures were followed as previously described (Section 3.2.3.2; Appendix 3.5).

6.2.3.6 Root sampling (2015)

Root sampling was carried out after the second harvest in 2015 only, according to the method previously described (Section 3.2.3.3; Appendix 3.5).

6.2.3.7 Harvest

The harvesting procedure was the same as previously used (Section 3.2.3.4). All leaf material was incorporated into the respective trial plots after the first harvest.

6.2.3.8 Statistical analysis

The same procedure as established for the previous trials was used (Section 3.2.3.5). Relative root yield and soil acidity indices were calculated using the following formulae:

Relative root yield (%) = (Root yield at a determined N x L rate / Maximum root yield at a determined N x L rate) × 100

Ca saturation (%) = (Ca²⁺ / CEC) × 100,

where CEC (as calculated) is the cation exchange capacity = $\sum(\text{Ca}^{2+}, \text{Mg}^{2+}, \text{K}^+, \text{H}^+, \text{Al}^{3+})$ in cmolc kg⁻¹

Mg saturation (%) = (Mg²⁺ / CEC) × 100

Acid saturation (%) = (H⁺+Al³⁺ / CEC) × 100

6.3 Results and discussion

6.3.1 Soil analysis

6.3.1.1 Soil properties

The soil has a loamy sand topsoil, with a low buffer capacity, and progressively increases in clay with depth (Table 6.1). Acid saturation is high in the topsoil (0-30 cm) but decreases with depth (Table 6.2), while pH and total cations increase with depth.

Table 6.1: Particle size distribution (%) for the diagnostic horizons of the Avalon soil form

Horizon* and depth (cm)	Clay (<0.002mm)	Fine silt (0.02- 0.002mm)	Coarse silt (0.05- 0.02mm)	Very fine sand (0.1- 0.05mm)	Fine sand (0.25- 0.1mm)	Medium sand (0.5- 0.25mm)	Coarse sand (2.0- 0.5mm)
A (0-30)	9.4	3.7	7.9	14.2	29.0	23.9	11.9
Yellow- brown apedal B (30-75)	20.2	4.6	6.5	13.8	24.9	19.0	11.0
Soft plinthic B (75-90)	27.3	4.9	7.4	12.4	19.9	16.3	11.8

* Soil Classification Working Group (1991).

Table 6.2: Mean soil chemical properties of the Avalon soil on the control plots before (n=4) (2013) and after (n=8) (2015) the trial

Initial soil sampling (2013) pre-trial														
Depth (cm)	Sample density (g mL⁻¹)	pH(KCl)	Acid sat (%)	Exch acidity (cmol L⁻¹)	Total cations (cmol L⁻¹)	P	K	Ca	Mg	Zn	Mn	Cu	Organic carbon (%)	N (%)
0 - 15	1.31	3.72	45	1.13	2.53	13	88	177	36	1.5	5	1.7	0.76	0.06
15 - 30	1.39	3.87	33	0.78	2.39	5	66	206	50	1.9	4	1.5	bdl [#]	bdl
30 - 45	1.36	4.12	9	0.31	3.43	2	73	411	107	1.0	3	1.6	bdl	bdl
45 - 60	1.31	4.71	2	0.10	4.92	1	57	577	218	0.3	2	1.6	0.08	0.04
60 - 75	1.25	5.04	1	0.08	5.57	1	71	612	274	0.2	2	1.3	0.09	0.05
75 - 90	1.24	5.29	2	0.09	5.09	1	73	463	304	0.7	10	1.1	0.17	0.09
Final soil sampling (2015) post-harvest														
0 - 15	1.30	4.63	4	0.12	3.36	48	215	398	85	4.0	3	1.3	0.96	0.11
15 - 30	1.35	4.46	5	0.12	3.44	24	99	440	112	4.0	3	1.8	0.81	0.07
30 - 45	1.35	4.58	3	0.12	3.78	3	48	443	160	0.3	1	1.6	0.40	0.05
45 - 60	1.31	4.53	5	0.21	3.73	3	65	392	170	0.2	3	1.2	0.45	0.03
60 - 75	1.25	4.53	5	0.20	3.80	5	77	347	204	0.8	4	1.5	0.49	0.08
75 - 90	1.24	5.30	2	0.09	5.09	1	75	460	307	0.7	11	1.1	0.17	0.08

bdl - Below detection limit

6.3.2 Yield

6.3.2.1 Addition of lime

Liming rate was moderately significantly correlated with root yield ($p=0.084$) (Appendix 6.1). The steep increase in response between L0 and L3 (Figure 6.1) is probably attributable to the Ca and Mg requirement of the crop. The initial pre-trial soil results showed a low Ca level of 177 mg L^{-1} and Mg of 36 mg L^{-1} . The effect of lime was more noticeable in the second harvest. Some early work by Allison and Sterling (1949) noted that with lime application more N was made available to a maize crop. Thompson et al. (1954) suggested that this N availability was only for a limited period of one season. In the present trial the highest yield independent of N was produced with L7 but with an interaction between lime and N (N200 x L3) L3 gave the highest yield (Appendix 6.1). The highest level of lime (L7) in conjunction with N200 depressed yield, but the reason for this is unknown. However, the difference between L7 only and the interaction of L3 with N200 was not significant. Root chicory seemed to show a high degree of resilience to increased nutrient conditions (L7 x N200). Tolerance to highly stressful nutrient conditions has been cited by Neel et al. (2002) who expressed chicory's ability to be akin to a "nutrient mop", while Sun et al. (2009) established that the crop was resilient to a 10% sea water concentration. Liang et al. (2015) identified a vacuolar Na^+/H^+ exchanger, CiNHX1 from chicory that plays a critical role in chicory's tolerance to salinity stress.

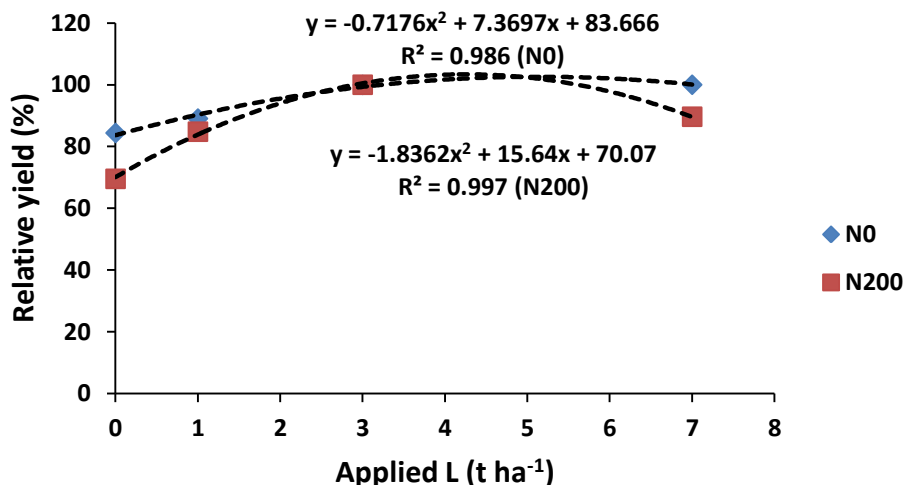


Figure 6.1: Mean ($n=8$) relative yield of root chicory in response to application of dolomitic lime (L) at zero and 200 kg ha^{-1} nitrogen (N0 and N200, respectively) (CV% 11.0, l.s.d. 12.766, S.E.M. 4.199 at $p<0.05$).

Soil Ca levels (after cultivation before planting chicory) were on average 192 mg L⁻¹ (0-30 cm) increasing with depth to 512 mg L⁻¹ (30-90 cm). After the final harvest, topsoil values from the N200 x L3 treatment had increased to 464 mg Ca L⁻¹ but the subsoil Ca value remained unchanged at 511 mg L⁻¹.

However, in the control plots the topsoil Ca increased from 192 to 419 mg L⁻¹ over time, while subsoil Ca decreased significantly from 516 mg L⁻¹ to 410 mg L⁻¹. This suggests that the chicory root might be utilising subsoil Ca in the absence of adequate topsoil Ca, as was the case with K (Chapter 4). It is surmised that chicory with its deep rooting system is able to supplement the nutrient supply in the topsoil with that from subsoil reserves.

6.3.2.2 Addition of ammonium sulphate

Root yield expressed as relative yield was moderately significantly increased by addition of ammonium sulphate in the second harvest only (p=0.068). With the addition of 7 t ha⁻¹ lime, maximum yield was obtained with 120 kg N ha⁻¹ and thereafter it decreased slightly with 200 kg N ha⁻¹ but this was not significant at the 5% level. The sharp response between 60 and 120 kg N ha⁻¹ with 7 t ha⁻¹ lime could, as before, relate to a response to the added Ca and Mg.

In fertiliser experiments, 90% of the relative yield is considered as an economic index (Fageria et al., 2010). The application of 1.5 t ha⁻¹ of dolomitic lime corresponded to a 90% relative yield. It is concluded that there was a moderate lime effect (p=0.084) with p=0.029 for the linear trend and a l.s.d. of 5.97. However, in this trial there was a poor response to N (as a main effect) which was non-significant. However, in time x applied N interaction (Table 6.3) comparisons there was a significant interaction and this suggests that N recommendations of between 60 and 200 kg N ha⁻¹ are justified from these trial results.

Table 6.3: Interaction of time x nitrogen (N kg ha⁻¹) on the mean yield of chicory (n=8) over two seasons

Time	N0	N60	N120	N200
Yield 2014 (t ha ⁻¹)	33.82	32.51	32.20	36.77
Yield 2015 (t ha ⁻¹)	37.58	44.23	42.77	44.93
Yield difference	3.76	11.72	10.57	8.16

CV% 11, l.s.d. 6.383, S.E.M. 4.199 at p<0.05

Since this trial site on recently worked land, and prior to this a long-term pasture (*Eragrostis curvula*), even in this loamy sand enough N will be released from the soil organic matter (SOM) for optimum yields without N fertiliser. However, the SOM-N depletes rapidly in sands but slower in clays. The interaction in Table 6.3 illustrates that SOM mineralisation released adequate N for maximum yield in the first season, and in the second there was less N mineralised, resulting in a significant response to N60. It is anticipated that in successive seasons a larger response to applied N compared to SOM would prevail. This finding is similar to that established by Nevens and Reheul (2001) who found that N release was highest during the first year decreasing during the second and third years following grassland ploughing on a sandy loam soil (similar soil texture to the trial site) in Belgium.

The results of this study are comparable with the results reported in Chapters 3 and 4 and with the literature for N requirements of root chicory under warm conditions (Moosavi, 2012; Seghatoleslami, 2014) but differ slightly from Patel et al. (2000) who only noted a significant response to 100 kg N ha⁻¹ and Khaghani et al. (2012) who did not use N levels >60 kg N ha⁻¹.

6.3.2.3 Effect of ammonium sulphate and lime application on soil acidity indices

Soil pH(KCl) significantly ($p < 0.001$) decreased with increasing nitrogen rate (0 to 200 kg N ha⁻¹) for the 0-15 cm depth (Figure 6.2, Appendix 6.2). The average decrease across both years in pH was from 4.8 at 0 N ha⁻¹ to 4.1 at 200 kg N ha⁻¹. The soil is low in buffering capacity and behaves like a weak acid, initially resisting sharp changes in pH. As more lime is added, more of the adsorbed Al is neutralised and replaced on the soil colloids mainly by Ca and Mg. There is a gradual increase in pH as a result, rather than an abrupt change. Decreases in soil pH have been reported by the use of ammonium sulphate (Hetrick and Schwab, 1992; Mulvaney et al., 1997; Bolan and Hedley, 2003; Fageria et al., 2010). Stumpe and Vlek (1991) reported that a decrease in pH of tropical soils (Oxisols, Ultisols, and Alfisols) due to the use of three N fertilisers was in the order of ammonium sulphate > urea > ammonium nitrate.

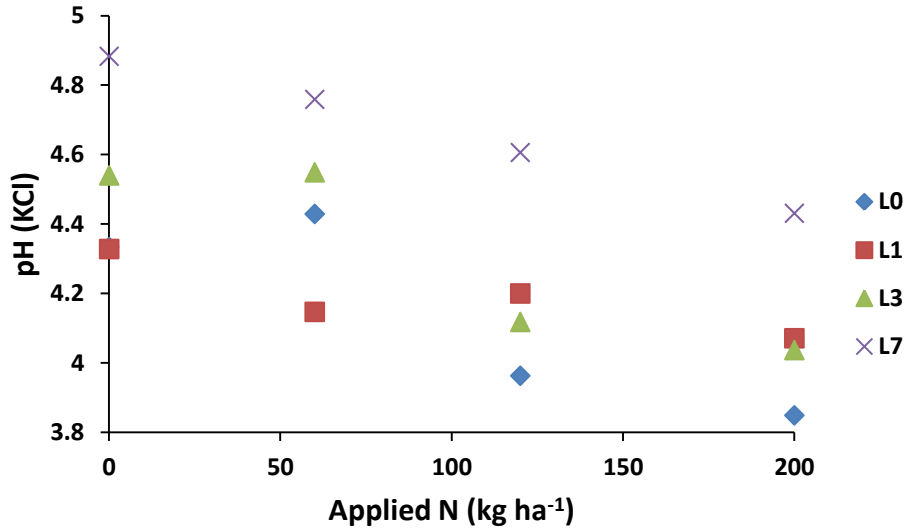


Figure 6.2: Mean (n=8) pH(KCl) in the 0-15 cm soil depth with the interaction of different levels of nitrogen (N) as ammonium sulphate at four lime (L) rates (t ha⁻¹) after two seasons (CV% 5.8, l.s.d. 0.5286, S.E.M. 0.2513 at p<0.05).

Calcium and Mg saturation with N200 applied decreased by 11.75 and 20.42%, respectively, compared with the control treatment. These decreases correspond with the increase in acidity at higher applied N rates.

The acid saturation increased (Appendix 6.2) and was highly significantly ($p < 0.001$) correlated to N application. The results of two years of ammonium sulphate fertilisation in the 0-15 cm soil depth are illustrated in Figure 6.3. It is apparent that at N rates of greater than 60 kg ha⁻¹ there is an upward trend in acid saturation percentage except for the L7 treatment. Acidification mainly occurs when there is loss of excess N as Ca and Mg nitrate (leaving the acidity behind). If the N is efficiently used by the crop, and none leaches, there will be far less acidification (Weil and Brady, 2016).

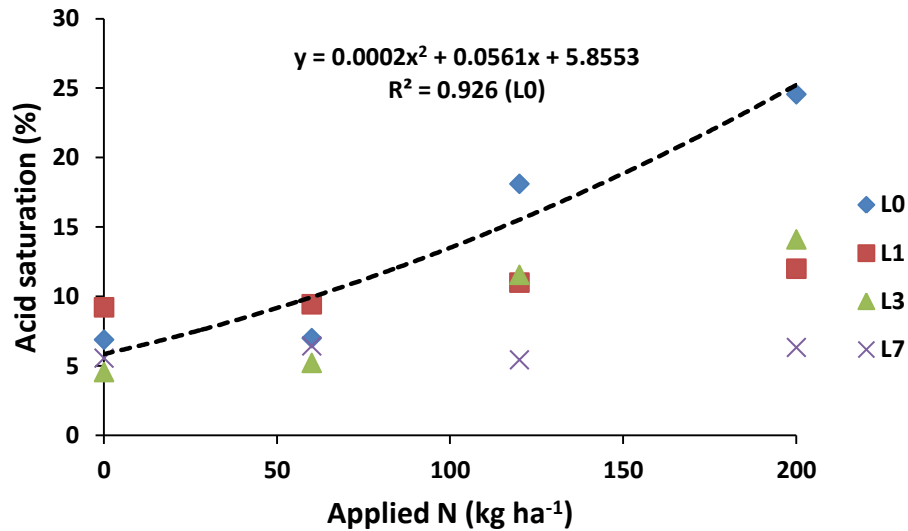


Figure 6.3: Mean (n=8) acid saturation in the 0-15 cm soil depth with the interaction of different levels of nitrogen (N) as ammonium sulphate at four lime (L) rates (t ha⁻¹) after two seasons (CV% 51.7, l.s.d. 11.676, S.E.M. 5.083 at p<0.05).

The lime rate was highly significantly correlated ($p < 0.001$) with pH, Ca and Mg after both harvests. Acid saturation and applied dolomitic lime had a probability of $p = 0.011$. Table 6.4 illustrates the rapid decrease in acid saturation from L0 to L1 and then a slower decrease in acid saturation percentage with a greater amount of added lime at L7. The difference between L1 and L7 pH results can be explained as proportionally more lime is required to attain very low levels of acid saturation in the soil. This results from a stronger buffering capacity at the lower acid saturation levels (Manson et al., 2012) and concurs with the findings from Chapter 3 (Section 3.3.3.2).

Table 6.4: Mean (n=8) pH (KCl) and acid saturation of the soil in response to four different levels of applied dolomitic lime (0-15 cm depth)

Lime (t ha ⁻¹)	pH	Acid saturation (%)
L0	4.27	14.14
L1	4.27	10.42
L3	4.42	8.86
L7	4.92	5.94

6.3.2.4 Relationship between soil acidity and root yield

The interaction of lime over time gave a significant difference in yield for all applied lime rates with the greatest difference at L1 (Table 6.5) but treatments L3 and L7 were also

significant. The greatest differences in yield were from L1 and L3. Response to lime was greater in 2015 (for the main effect of lime $p=0.009$) than in 2014 ($p=0.189$).

Table 6.5: Interaction of time x lime (L t ha⁻¹) on the mean yield of chicory (n=8) over two seasons

Time	L0	L1	L3	L7
Yield 2014 (t ha ⁻¹)	32.81	29.97	35.54	36.97
Yield 2015 (t ha ⁻¹)	36.08	42.72	46.06	44.66
Difference in yield	3.27	12.75	10.52	7.69

CV% 11.0, l.s.d. 6.383, S.E.M. 4.199 at $p<0.05$

6.3.2.5 Change in topsoil chemistry over time

Trial results show a significant change in soil chemistry of the control treatment over time (Table 6.2). The trial was irrigated using information from soil tensiometers for the period under study and the soil chemical properties at the end of the trial are given in Table 6.2. No irrigation had been used on this site prior to the trial being established. It can be observed (Table 6.2) that the top 30 cm of soil was highly acidic, the result of a combination of fertilisation, leaching of bases and perhaps the oxidation of ferric iron. The soil changes dramatically from 30 to 90 cm as it becomes less acidic with an increase in the CEC and clay with depth. In the 75 to 90 cm zone there are visible signs of alternating reduction and oxidation. The acidity in the upper 30 cm of the soil on the control plots, at trial completion, decreased accompanied by an increase in the CEC. This may be explained partly by the incorporation of single superphosphate to the plots. However, even in plots treated with ammonium sulphate a decrease in acidity was noted, but the effect of this N form was still evident after the second harvest but at lower acidity values.

There are a few possible explanations for this phenomenon. In the first instance the soil at the trial site has a soft plinthic B-horizon. The formation of this horizon is related to the process of ferrollysis (Brinkman, 1970) which involves the oxidation and reduction of iron. The seasonal nature of the fluctuating water table creates cycles of aerobic and anaerobic conditions. The reduction phase sees the formation of ferrous iron which displaces base cations from the exchange sites. Leaching of these base cations from the soil with bicarbonate from biotic respiration can be concentrated at the depth of leaching. These reduction reactions consume protons (H⁺) resulting in an increase in soil pH during this period. During the oxidation phase the ferrous iron is changed to insoluble ferric iron (manifested as mainly red

or yellow mottles set in a grey matrix) producing protons which acidify the soil contributing to a low base saturation and pH (Brinkman, 1970, 1977; Van Breemen et al., 1983). The resulting soft plinthic B- horizon is only slowly permeable (Jennings et al., 2008) and leads to a perching of water resulting in the yellow-brown apedal B- horizon above it. These processes are a possible explanation for the formation of the Avalon soil form under the prevailing climatic conditions (Le Roux et al., 2005). However, the advent of irrigation could have resulted in a longer reduction phase occurring in a greater volume of soil above the soft plinthic B-horizon into the yellow-brown apedal B-horizon and orthic topsoil with the resultant chemical changes occurring in the 0-30 cm depth inducing a decrease in acidity.

Secondly, it is also known that soils near the trial have subsoils that are often saturated with Na (Edwards, 1967). Manson (2000) suggests that the uptake of Na below 30 cm via Na/H antiport, and subsequent efflux of Na (via Na/H antiport) in the topsoil would effectively transfer alkalinity upwards.

Various researchers have observed changes over time with the addition of irrigation. Verster and van Rooyen (1993) noted a change of selected soil properties, over a 25-year period under intensive irrigation at the Hardap irrigation scheme in southern Namibia. Among the changes, extractable cation composition, colour and an improvement in soil salinity (on well-drained soil profiles) were noted. Mon et al. (2007) in the Pampa region of Argentina observed a slight increase in sodication and alkanisation in a 10 year period of supplementary irrigation. Heck et al. (2003) also described an increase in salinity levels that tripled under canopy cover of a mango (*Mangifera indica* L.) grove after five years despite excellent water quality from the São Francisco River Valley, Brazil. The mango grove had a very saline and sodic groundwater table.

Thirdly, the possibility also exists of root chicory increasing the pH of the growth medium, and thus reducing Al solubility and toxicity to explain the change in circumstances with the deep-rooted chicory extracting Ca, Mg, K and Na from the subsoil. Witter and Johansson (2001) reported that chicory was able to use up to 80 kg K ha⁻¹ from the subsoil (Section 4.3.2.2).

Related to this root-driven process, on the cation-anion balance in plants and its relation to ion accumulation and changes in rhizosphere pH (as critically reviewed by Haynes (1990)) further research into the effect of the rhizosphere on soil solution has been the subject of

considerable study in recent years (Hinsinger, 2001; Dakora and Phillips, 2002; Hinsinger et al., 2003; Walker et al., 2003; McGahan et al., 2014). It is known that rhizosphere properties differ from those of bulk soil however; differences are not always predictable and may be influenced by the kinds of plant roots and by soil mineral composition. Findings indicate that dicotyledons (e.g. chicory) differ from monocotyledons in their rhizosphere effects (McGahan et al., 2014) and change the rhizosphere more than monocotyledons, relative to bulk soil.

Working on barley and soybean Youssef and Chino (1989) presented research results that showed that alkalisation in the rhizosphere at an initially low pH of 4.8 occurred, while they noted that acidification occurred when pH values were initially 7.1. They found that there was almost a 2 pH unit difference in a zone 2-3 mm from the root surface. Chaignon et al. (2002) found alkalisation in an acidic soil and acidification in a calcareous soil in the rhizosphere of oilseed rape (*Brassica napus* L.) and tomato (*Solanum lycopersicum* L.). Schubert et al. (1990) established that a given plant species caused different changes in soil pH according to the pH buffering capacity of the soil; the greater the pH buffering capacity, the smaller the plant-induced pH change. Just how these pH changes take place is yet not that clearly understood but a number of plant species act as if their roots modify their environment to produce soil with a more acceptable pH. From the results of the present trial, it appears that root chicory could be another of these plant species.

It is concluded that a combination of processes could have resulted in the change in topsoil (0-30 cm) chemistry and further investigation is required.

6.3.3 Leaf analysis

This section reports the average of the leaf samplings taken at 60 DAS and at 220 DAS (at harvest) for the two cropping years. The 60 DAS leaf sampling is reported unless otherwise stated.

6.3.3.1 Effect of lime

It has been reported (Fu et al., 1987; Clay et al., 1993) that, with the addition of lime, a temporary soil N increase results. However, in the present trial, this effect was not significant in either year. The addition of lime produced statistically significant associations with B, Ca,

copper (Cu), manganese (Mn), P and zinc (Zn) (Appendix 6.3). Leaf B gave an initial negative response to 1 t lime ha⁻¹, and then responded positively with 3 t lime ha⁻¹ thereafter decreasing with the addition of 7 t lime ha⁻¹. The mean for the control plots was 17.4 mg B kg⁻¹ while at the high lime rate 17.3 mg B kg⁻¹ was recorded. The higher yielding root plots (>35 t ha⁻¹) had a leaf B level of >21 mg B kg⁻¹ (Table 6.5). Prolonged exposure to low B (<20 mg B kg⁻¹) is known to be a precursor for the formation of heart rot (Van Hee and Bockstaele, 1983) and was discussed in Section 5.3.1.

As expected, leaf Ca increased with lime application and the crop reacted significantly at $p < 0.05$ to its application and it was significantly positively correlated to yield. The turning point was 3 t lime ha⁻¹ before slowly decreasing to 7 t ha⁻¹, probably due to the change in pH and the effect on the availability of other elements to the crop. The leaf Ca level from the control plots was 0.9% while that at the highest lime level (L7) was on average 1.0% and effectively the same across the lime treatments. The highest yielding plots had a leaf Ca level of 0.9%.

Leaf Cu responded negatively to a lime increase with 18.2 mg kg⁻¹ recorded on average in the control plots and 16.3 mg kg⁻¹ in the high lime plots. The leaves from the higher yielding plots had a Cu level of 16.9 mg kg⁻¹. Leaf Mn also responded negatively to lime treatment with 167.4 mg Mn kg⁻¹ recorded in the control plots and 95.9 mg Mn kg⁻¹ in the high lime plots. The highest Mn in the leaf was 132.6 mg Mn kg⁻¹ obtained from the highest yielding plots (47.50 t ha⁻¹). Leaf Zn also decreased with an increase in lime. The control plot levels were on average 83.4 mg kg⁻¹ while at the highest lime application rate 58.1 mg kg⁻¹ was recorded. Phosphorus levels in the leaf responded positively to the increase in lime with 0.29% P recorded for the control plots and 0.32% P for the L7 plots. The highest average wet root yield (47.50 t ha⁻¹) was obtained with a leaf P of 0.31% P (Table 6.6).

Table 6.6: Leaf, and root analysis at the 2015 harvest (in italics), over the four leaf sampling times indicating the range over lime (L) x nitrogen (N) treatments, the grand mean (n=8) per element analysed for the two harvests and the values at the highest yield obtained for lime applied at 3 t ha⁻¹ and N applied at 200 kg ha⁻¹ (L3 x N200)

Element	Range over LxN treatments	Grand mean	Highest yield value (L3 x N200)
Aluminium (mg kg ⁻¹)	2 568-3 764 (<i>577-1101</i>)	3 100 (<i>682</i>)	3 443 (<i>627</i>)
Boron (mg kg ⁻¹)	15.28-21.20 (<i>6.29-8.11</i>)	17.40 (<i>7.25</i>)	21.20 (<i>8.11</i>)
Calcium (%)	0.78-1.05 (<i>0.15-0.18</i>)	0.90 (<i>0.16</i>)	0.90 (<i>0.17</i>)
Copper (mg kg ⁻¹)	15.62-19.72 (<i>9.54-11.86</i>)	17.5 (<i>10.52</i>)	10.52 (<i>11.46</i>)
Iron (mg kg ⁻¹)	1 247-1 935 (<i>408-816</i>)	1 565 (<i>538</i>)	1 647 (<i>514</i>)
Magnesium (%)	0.35-0.40 (<i>0.94-0.12</i>)	0.40 (<i>0.10</i>)	0.36 (<i>0.12</i>)
Manganese (mg kg ⁻¹)	81.90-219.21 (<i>20.40-56.20</i>)	133.4 (<i>32.10</i>)	132.6 (<i>37.4</i>)
Nitrogen (%)	2.89-3.40 (<i>0.69-1.02</i>)	3.20 (<i>0.82</i>)	3.40 (<i>1.02</i>)
Phosphorus (%)	0.28-0.32 (<i>0.18-0.24</i>)	0.30 (<i>0.22</i>)	0.31 (<i>0.24</i>)
Potassium (%)	4.35-5.00 (<i>1.14-1.51</i>)	4.70 (<i>1.41</i>)	4.68 (<i>1.51</i>)
Sodium (mg kg ⁻¹)	8 794-11 954 (<i>2768-3767</i>)	10 281 (<i>3358</i>)	9 732 (<i>3058</i>)
Sulphur (%)	0.42-0.50 (<i>0.10-0.12</i>)	0.50 (<i>0.11</i>)	0.50 (<i>0.12</i>)
Zinc (mg kg ⁻¹)	55.4-104.70 (<i>23.00-33.79</i>)	71.10 (<i>28.83</i>)	74.20 (<i>30.35</i>)

6.3.3.2 Effect of ammonium sulphate

The addition of ammonium sulphate only produced statistically significant effects on leaf Cu, N, and S.

Copper increased from 16.7 mg kg⁻¹ in the control plots to 18.1 mg kg⁻¹ at the highest N level (200 kg N ha⁻¹). The highest wet root yield (47.50 t ha⁻¹) was obtained with 16.9 mg Cu kg⁻¹. Nitrogen in the leaf, as would be expected, was highly significantly correlated with the amount of ammonium sulphate applied with 3.0% found in the control plots and 3.4% at the highest level of N application. The highest yield was also achieved with 3.4% N recorded in the leaf. Sulphur showed a positive correlation with N over time. The interaction of N with time on leaf S was moderately significant at p=0.013. There was a general increase in leaf S from 0.4% in the control plots to 0.5% at 120 kg N ha⁻¹ and then a marginal decrease at 200

kg N ha⁻¹. This can be attributed to the S added by the ammonium sulphate (24% S) in addition to that present in the superphosphate (13% S).

6.3.3.3 Relationship between leaf analysis and yield

Table 6.6 gives the concentrations of elements in the leaves at L3 x N200, which gave the highest average wet root yield (47.5 t ha⁻¹).

Boron levels were once again generally lower than that desired for crops (>25 mg B kg⁻¹) (Shorrocks, 1997), even with the soil application of 2 kg B ha⁻¹, indicating its tendency to leach (Chapter 5). Regular foliar application might have possibly been a better option to allow for a presence of B on the leaf as well as from wash-off over time (Chapter 5) in the topsoil. Yield was not significantly related to leaf B, as was the case from the findings in Chapter 5. Manganese levels in the leaf are considered to be relatively high (Hochmuth et al., 1993, 2009) but did not appear to have any negative effect on yield. Leaf P did not appear to be related to root yield; this was also found in the N x P x L trial (Chapter 3). Yield could have been significantly affected by the addition of S but it was confounded with the application application of ammonium sulphate and single superphosphate. An S level of 0.5% is at the upper end of the normal range (Hochmuth et al., 1993, 2009). Traditionally S levels are low in the sandy loam topsoils on the sandstone geology of the area surrounding the trial site. Zinc levels in the leaf from all the treatments are regarded by Hochmuth et al. (2009) as normal (25-150 ppm) for a wide variety of vegetable crops.

It should also be noted that root chicory was able to produce a high yield at L7 x N200 with only a relative decrease of 1.48% from the highest yield measured with L3 x N200. Other crops, such as maize, show a much larger yield depression when a high rate of lime is applied to a low clay content soil (Claassen, 1971; Dhliwayo et al., 1998; Busari et al., 2008). This illustrates the ability of root chicory to withstand a relatively high lime application rate (as confirmed by the N x P x L trial, Chapter 3) indicating its tolerance of higher CEC and pH conditions. Similar findings have been found by other researchers but working on forage chicory (Neel et al., 2002; Sun et al., 2009).

6.3.4 Root analysis

In general, approximately 80% of all nutrients absorbed by roots are translocated to the shoots (Hochmuth et al., 1993, 2009). The low values of the elements analysed (Table 6.6) when compared to those in the leaves (Table 6.6) illustrates this.

6.3.4.1 Effect of lime

There was a similarity between the root and leaf analysis with lime as both showed statistically significant responses with to B, Mn, P and Zn (Appendix 6.4). In addition, lime had significant effects on Na, K and Al in the root. This is similar to the results found in the N x P x L trial. The different lime treatments did not have a significant effect on Ca or Mg in the root in contrast with the leaf data where Ca was significant. Calcium is considered an immobile nutrient (Mortvedt et al., 1972; Hochmuth et al., 2009) and is held in relatively permanent constituents of plant compounds such as cell walls. Transpiration is an important process for the transportation of Ca as it moves towards areas of high transpiration (rapidly expanding leaves). The region of the root just behind the root tip is considered to be the area where Ca uptake is highest (Hochmuth et al., 2009). Magnesium, compared to Ca, is absorbed in lower amounts and unlike Ca is highly mobile in the plant (Hochmuth et al., 2009).

6.3.4.2 Effect of ammonium sulphate

The different ammonium sulphate treatments only resulted in a statistically significant effect on Mn with an increase from 30.4 mg kg⁻¹ in the roots from the control plots to 37.4 mg kg⁻¹ in the N200 treatment, which also corresponded to the highest yield. This was most likely due to the acidic nature of ammonium sulphate that made Mn more available.

6.3.4.3 Relationship between root analysis and highest yield

Aluminium decreased significantly with the application of lime and increased with N treatment but this was not significant despite a wide range in measured Al values (Table 6.6). The lower the measured values, the higher the yield although below 600 mg Al kg⁻¹ yields were depressed, even when higher lime (L7) was supplied with N200. A decline in B was not noted as would have been expected due to the high amount of lime applied. There was a decrease in Fe at L7 (500 mg kg⁻¹) and yield decreased slightly with the application of N200.

Potassium decreased at the L7 treatment to 1.46% K. At less than 37 mg Mn kg⁻¹ yield decreased slightly with L7. Sodium decreased with the addition of N, and lime (up to 3 t ha⁻¹) thereafter increasing with the application of L7. At L7 P again declined accompanied by a slight decrease in root yield. Zinc increased with increasing application of N but decreased with increasing lime application. A Zn concentration of 30 mg kg⁻¹ was the optimal amount for the highest yield.

RTFA (2015) reports on Dutch research norms (Sarrazyn and Deckers, 1991) for chicon production (regrowing of the central bud on chicory roots in the following season) for the best forcing yields. As these are the only criteria given in the literature on roots at first year harvest it will be used to compare to the results from the trial (Table 6.7).

Table 6.7: Dutch norms (RTFA, 2015) for chicory roots at harvest compared to mean (n=8) lime (3 t ha⁻¹) x nitrogen (200 kg ha⁻¹) treatment trial results

	Dutch norms (%)	Trial (%)
Nitrogen	0.70 - 1.30	1.02
Phosphorus	0.23 - 0.28	0.24
Potassium	1.50 - 2.0	1.51
Calcium	0.27 - 0.29	0.17
Magnesium	0.13 - 0.15	0.12

Nitrogen is within the range of the Dutch norm while average P and K values are just within the norms and Mg is slightly lower. Calcium, however, is lower than the norm by a substantial margin. The results given in Table 6.7 are from a treatment receiving 3 t ha⁻¹ dolomitic lime and suggest that the available soil Ca levels are still inadequate for the crop. However, the higher rate of 7 t ha⁻¹ dolomitic lime only increased root calcium to 0.18%.

Adams and Ho (1993) observed environmental influences on Ca uptake in tomatoes and its relation to blossom-end rot in the United Kingdom. They reported that Ca uptake was highly correlated to solar radiation and root temperature while high humidity reduced Ca import by the leaves but increased that by the fruit.

A large portion of the non-uran area of The Netherlands is dominated by marine clays (24%) (Hartemink and Sonneveld, 2013) that have a high pH and is an area where chicory is planted

(Sarrazyn and Deckers, 1991). An analysis of soil from Lelystad in the Netherlands indicates that clay soils from the area have a high pH(KCl) 7.2 and suggests a high calcium level (Velthof and Oenema, 1995). Chicory has the capability to do well on these types of soils provided they are adequately drained. These marine clay soil types provide a different soil chemical environment than that studied in KZN. It is possible that differences in environmental variables between those in The Netherlands and the trial site might have resulted in the consistently lower Ca levels found on the DARS trial soils in KZN.

It is apparent that despite high rates of Ca applied on this DARS soil type, root chicory required more Ca or responded differently to applied Ca than Ca from the natural environment. In Chapter 7, soils with different texture and clay mineralogies are examined and the possible soil types that show root Ca levels as suggested by the Dutch norms are indicated. This aspect is considered further in Chapter 7.

6.4 Conclusion

6.4.1 Yield

The relative yield of root chicory was increased significantly by the application of N applied as ammonium sulphate over time. The highest lime application of 7 t ha⁻¹ with 200 kg N ha⁻¹ showed only a marginally lower relative yield (89.64%), illustrating the tolerance of root chicory to high lime levels and pH. Improved chicory yield at even 1 t ha⁻¹ of lime suggests a response to Ca and Mg as nutrients due to the low initial soil levels.

6.4.2 Soil

Root yield was not affected by the increase in acid saturation from 6.89 to 24.56% at N200 using ammonium sulphate and showed a positive response to the N source over the two harvests. Root yield was also non-significantly positively associated with pH, Ca, Mg and base saturation levels. These relationships indicate that root chicory is tolerant to at least this acid saturation range. With increasing lime application, significant effects on Ca, Mn and acidity over time and depth were observed.

Despite the addition of high amounts of ammonium sulphate (200 kg N ha⁻¹), soil acidity decreased over the two harvests although it did show an upward trend with increasing ammonium sulphate application. Possible causes for this were the degradation of the silicate

clay material under varying redox conditions (ferrolysis) leading to changes in soil chemistry and root specific influences whereby root chicory is able to increase soil pH thereby reducing Al solubility and toxicity by extracting deeper reserves of Ca, Mg, K and Na from the subsoil. In addition there are also possible direct rhizosphere effects on soil pH by the crop.

6.4.3 Leaf

The addition of lime produced statistically significant responses to leaf B, Ca, Cu, Mn, P and Zn. Nitrogen applied as ammonium sulphate produced statistically significant responses with Cu and S as a result of a more acidic environment that favoured the release of these elements, and additionally for S, due to it being added to the soil as a fertiliser amendment for plant uptake.

6.4.4 Root

Liming had a significant effect on Al, B, Fe, K, Mn, Na, P and Zn. The different lime treatments did not have a significant effect on Ca in contrast with the leaf data where Ca was significant. There was a similarity between the root and leaf analysis with applied lime as both showed statistically significant responses with B, Mn, P and Zn. The roots had lower nutrient accumulation than in the leaf with an average leaf : root ratio of 3.2 : 1 across all elements analysed and is similar to the N x P x L trial (Chapter 3).

The hypothesis that ammonium sulphate would acidify the soil sufficiently to have an effect on the yield of the root chicory crop grown was rejected at $p < 0.05$ on the trial soil under irrigation management.

CHAPTER 7

POTASSIUM BEHAVIOUR IN SOIL AND RESPONSE OF ROOT CHICORY (*Cichorium intybus* var. *sativum*) TO APPLIED POTASSIUM IN A POT EXPERIMENT

7.1 Introduction

Potassium (K), one of the major plant macronutrients, is vital to many plant processes. It activates many enzyme systems, maintains turgor, aids photosynthesis, enhances translocation of sugars and starch, retards crop diseases and is important for root growth and drought resistance (Epstein and Bloom, 2005; Römheld and Kirkby, 2010; Bukhsh et al. 2012).

Potassium is always present as the K^+ ion in soils, but it is found in several forms i.e., (1) solution K, (2) exchangeable K held on cation exchange sites, both of these forms are readily plant-available (Reitemeier, 1951; Sparks 2001; Römheld and Kirkby, 2010); (3) potassium in pylosilicateminerals interlayers, a portion of which is plant-available, depending on soil clay mineralogy (Wood and DeTurk, 1941; Reitemeier, 1951; Rich, 1968; Johnston and Goulding, 1990; Sparks 2001); and (4) matrix-K in minerals such as micas and feldspars, which is not plant-available except over long time periods (Reitemeier, 1951; Rich, 1968; Martin and Sparks, 1985; Snäll and Liljefors, 2000). Of this total K content, typically 90-98% is bound in the mineral form, and only 1-2% is in soil solution and exchangeable phases (Schroeder, 1979; Bertsch and Thomas, 1985; Römheld and Kirkby, 2010).

The concentration of K in the soil solution depends upon the balance of exchangeable cations and the concentration of anions in the soil solution. This is modified by plant uptake, depending on the rate of removal by the plants and the speed at which K can be desorbed from the adsorbed phase. Potassium desorption is controlled by the mineral composition, rate of weathering and exchange properties of the soil. The initial adsorption equilibrium solution K concentration serves as an index of K availability. Thus equilibrium K concentration appears to provide a better index of soil fertility (Singh and Jones, 1975) than traditional soil K extractant methods. Knowledge of the variation in K adsorption among soils and the equilibrium between intensity and quantity phases of soil K is necessary to predict the fate of applied K fertilisers in soils and so make accurate K fertiliser recommendations (Sparks and Huang, 1985; Hinsinger, 2002). Potassium requirements for a crop can vary to a large degree

depending on the mineralogical composition of the soil. Understanding how K application can be managed efficiently on different soil types provides many challenges to researchers and growers alike.

Root chicory has the ability to utilise K from the subsoil and fertiliser recommendation cannot be based solely on topsoil results (Chapter 4). The field experiments answered a number of questions on root chicory's response to varying K treatments regarding yield, soil, leaf and root characteristics. This information is valuable for those growers using similar soils, but many areas used for root chicory have different soils. How the plant reacts to varying K application rates in soils of different texture and clay mineralogy is not clearly understood and so a pot trial was designed to include a variety of soils to accommodate some of these planting areas.

The K isotherm technique (Quantity / Intensity (Q/I) relationship) was used to determine K levels before and after the pot trial and its availability for root chicory was examined using the Freundlich (1906), Langmuir (1918) and Temkin (1940) equations. The hypothesis that soil type, especially soil texture and clay mineralogy, plays a significant role ($p < 0.05$) in K behaviour and K fertiliser management was proposed. From the standpoint of the chicory growers in KwaZulu-Natal (KZN) soil texture is a fundamental variable and so formed the foundation for this study.

7.2 Materials and Methods

7.2.1 Soils

Initially a batch of 17 soils from potential chicory growing areas in KZN were sampled and analysed for clay mineralogy by X-ray diffraction (Appendix 7.1 and 7.2), total elements by X-ray fluorescence spectrometry (Appendix 7.3), texture and chemical analysis. From these soils, five were selected that covered a range of textures, clay mineralogy and chemical properties. These soils came from near Utrecht, the Dundee Agricultural Research Station (DARS) and Nkaseni, near Weenen (Figure 7.1).

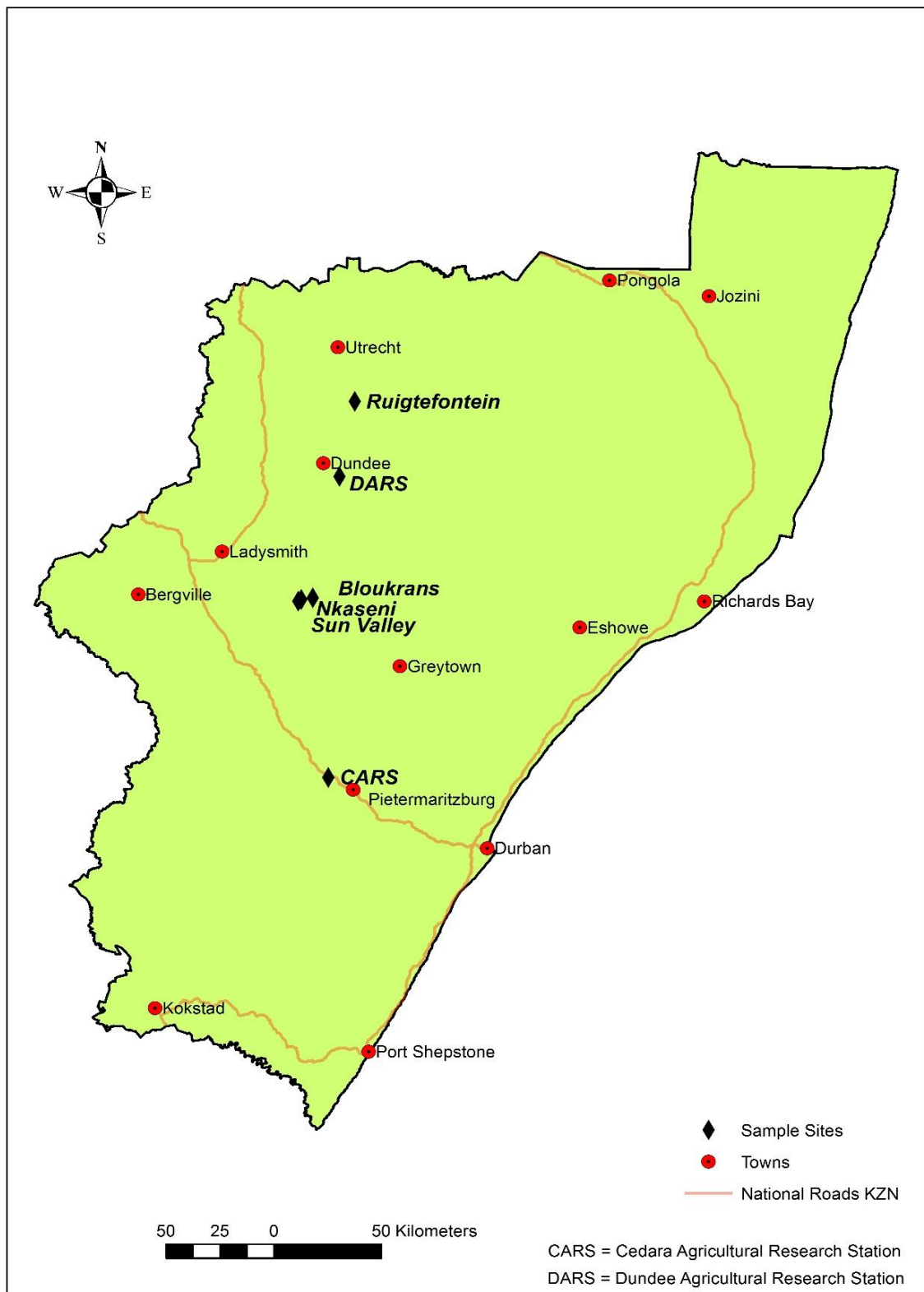


Figure 7.1: Location of the five sampling sites and the experimental site (Cedara Agricultural Research Station) in KwaZulu-Natal.

The soils (with their classification according to the Soil Classification Working Group, 1991) are subsequently referred to by their location as follows:

1. DARS - (approximately 10 km north-east of Dundee; 275349.4 S; 301147.2 E); an Avalon soil form; Blackmoor 1100 family; Typic Plinthaquult.
2. Ruigtefontein – (approximately 15 km south of Utrecht; 275349.4 S; 302402.0 E) a Dundee soil form; Nonoti 1110 family; Fluventic Dystrudept.
3. Bloukrans (approximately 5 km west of Nkaseni; 284518.0 S; 301147.2 E) a Sepane soil form; Ramabesa 1220 family; Typic Endoaqualf.
4. Nkaseni (approximately 15 km north-east of Weenen; 284544.4 S; 300828.2 E) an Inhoek soil form; Shingwedzi 1200 family; Entic Haplustoll.
5. Sun Valley (approximately 6 km south-west of Nkaseni; 284610.5 S; 300739.1 E) a Swartland soil form; Burgersdorp 1212 family; Typic Rhodustalf.

On finalisation of the selection of the five soils, representative topsoils (0-30 cm) were excavated using a spade and collected in clean, labelled 210-L plastic drums and transported to the Cedara Agricultural Research Station (CARS) where they were air-dried and milled (<2 mm).

7.2.2 Laboratory analyses

7.2.2.1 Slowly available potassium (nitric K)

Soil (2.5 g) was extracted with 100 mL of boiling nitric acid for 30 minutes (Haysom, 1971) on a hot plate. This extract was filtered through a Whatman No. 1 filter paper and diluted with deionized water to 200 mL. The K was measured by inductively coupled plasma (ICP Varian Vista-MPX®). Reported nitric K values were corrected for exchangeable potassium.

7.2.2.2 Potassium isotherms

For the construction of K adsorption isotherms, duplicate 5 g soil samples were sieved (<1 mm) and equilibrated with different K concentrations (0, 50, 100, 150, 200 and 250 $\mu\text{g mL}^{-1}$) in a 50 mL solution of 0.01M CaCl_2 at $25\pm 1^\circ\text{C}$ for 24 hours. Three drops of toluene were added to each sample to prevent bacterial growth. Samples were shaken on an end-over-end shaker (Labcon SPO-MP8®) for 24 hours at 200 r.p.m. in a temperature-controlled room (25°C). Thereafter samples were centrifuged at 2 000 r.p.m. for 20 minutes after which

they were filtered through a Whatman No. 1 filter paper. Potassium in the filtrate was analysed by atomic absorption spectrophotometry (Varian AA280FS®). The amount of K adsorbed was determined by Equation 7.1.

$$\Delta K = (CK_i - CK_f) / (V/W) \dots \dots \dots \text{Equation 7.1}$$

where: ΔK is the change of K in soil solution; CK_i is the initial K concentration added (mg kg^{-1}); CK_f is the final equilibrium concentration of K in solution, V is the solution volume (mL); W is the soil mass (mg).

Positive ΔK values indicate adsorption by the soil solid phase; negative values indicate desorption by the soil. The K adsorption data were fitted into linearized forms of the Freundlich, Langmuir and Temkin adsorption models (Equations 7.2 to 7.7).

Field K fertiliser application rates were calculated based on the Freundlich model for various target levels of soil solution potassium (0, 6, 12, 18, 24, and 27 mg L^{-1}).

Freundlich

$$x/m = a C^b \dots \dots \dots \text{Equation 7.2}$$

By rearrangement:

$$\log (x/m) = \log a + b \log C \dots \dots \dots \text{Equation 7.3}$$

where: x/m is the mass of K adsorbed per unit mass of soil (mg kg^{-1}); C is the equilibrium solution K concentration (mg L^{-1}); a and b are constants obtained from the intercept and slope, respectively.

Use of this model provided K fertilisation rates calculated as follows (Hannan et al., 2011; Kenyanya et al., 2014):

$$\text{Fertiliser quantity } q_e (\text{mg kg}^{-1}) = aC_e^b \text{ or antilog } (\log x/m + \log EKC) \dots \dots \dots \text{Equation 7.4}$$

where: EKC is the specific soil solution K (mg L^{-1}) required.

$$\text{Fertiliser quantity } (\text{kg ha}^{-1}) = \text{Fertiliser quantity } q_e (\text{mg kg}^{-1}) \times 2 \dots \dots \dots \text{Equation 7.5}$$

where: q_e is the amount of potassium adsorbed per unit mass of soil.

Langmuir

$$C / (x/m) = 1/kb + C/b \dots\dots\dots\text{Equation 7.6}$$

where C and x/m have the same meaning as for the Freundlich equation; k is a constant related to the bonding energy of K to the soil; and b is the maximum K adsorption capacity of the soil.

Temkin

$$x/m = a + b \ln C \dots\dots\dots\text{Equation 7.7}$$

where the symbols have the same meaning as for the Freundlich equation.

7.2.2.3 Water analysis

The water used for irrigating the pots was analysed using the prescribed methodology for water analysis at CARS (Manson and Roberts, 2001) on three different occasions to determine the mean water quality (Appendix 7.4).

7.2.3 Site and trial design

7.2.3.1 Site

The trial was conducted at CARS in a growth tunnel. The temperature and humidity were thermostatically controlled and consisted of two wet walls with two extractor fans and mist sprayers. No artificial lighting was used. Temperature was maintained at 26°C during the daytime while night temperatures were not controlled and varied from 5 to 22°C.

7.2.3.2 Trial design

Layout and fertiliser treatments

The trial was arranged in a randomised block design consisting of six K treatments on five different soils with three replications. Initially the soils from DARS, Bloukrans, Nkaseni and Sun Valley were planted in draining, plastic 45 cm deep, 25 L containers to soybeans for three harvests over a period of 20 weeks to reduce the amount of exchangeable K. The soil from Ruigtefontein was very low in exchangeable K (23 mg L⁻¹) and was not planted to soybeans.

After the three soybean harvests the four soils were again analysed to determine the remaining exchangeable K status. Root chicory was then planted in all the pots which were filled according to field bulk density (Table 7.1) at six treatment levels (0, 50, 100, 150, 200, and 250 kg K ha⁻¹) spread and worked in as potassium chloride (KCl) (52% K) and subsequently referred to as K0, K50, K100, K150, K200 and K250. Nitrogen (N) was added at a standard rate of 160 kg ha⁻¹ to all pots at planting as limestone ammonium nitrate LAN (28% N). All soils had adequate phosphorus (P), using beetroot fertiliser guidelines (Manson et al., 2012) as a proxy, except for the Ruigtefontein sample which received 184 kg P ha⁻¹ using single superphosphate (10.5% P, 13% S). In addition, the Ruigtefontein and DARS soils were low in calcium (Ca) and magnesium (Mg) and this was rectified with an appropriate amount of dolomitic lime to an acid saturation of 5%, again according to beetroot fertiliser guidelines (Manson et al., 2012).

Table 7.1: Bulk densities of the five soils

Soil	Bulk density (g cm ⁻³)
DARS	1.59
Ruigtefontein	1.60
Bloukrans	1.00
Nkaseni	1.04
Sun Valley	1.08

Soil preparation

Prior to planting, soil was worked with a small hand fork. The Ruigtefontein and DARS soils provided an easy soil surface within which to plant due to their low clay content. For the higher clay content soils, a 10 mm layer of inert quartz sand was placed on the soil surface to aid planting and germination.

Planting and thinning

Chicory seeds of the variety *Orchies* were planted on the 5 November 2015. At 45 days after sowing (DAS) plants were thinned to two plants per container.

Watering

The soils were drip irrigated using an automated system to keep them at field capacity as determined by ten soil tensiometers (five each at 6 and 12 cm soil depths) (Irrrometer MLT 6 and 12®) with two placed in each soil type at each depth. Pots had a tank bung at the base with a stepped reducer for a pipe attachment. Leachate was collected in a plastic container (5 L) via a 15 mm flexible pipe under the pot and returned to the treatment pot when the leachate container had received approximately 500 mL (Plate 7.1).

Weeding

Weeding was done until the chicory had adequately covered the soil surface (at about 60 DAS). After this weeding was unnecessary as competition from weeds was minimal.

Micronutrient leaf spraying

At 60 DAS the chicory plants received a broad spectrum micronutrient spray (Trelmix®) every two weeks until harvest to eliminate any possible micronutrient deficiencies. An electric 12 volt Kobold knapsack sprayer (KB-16E-3®) was used at a pressure of 200 kPa.



Plate 7.1: Method of leachate collection from the pots.

Leaf sampling

The first leaf sampling was done at 60 DAS and repeated at 120 DAS and at harvest (180 DAS; 5 May 2016) to determine K uptake in the leaf over the growing period.

Harvest

At harvest, wet leaf mass (of the two plants in each pot) was measured, and leaf and root samples taken according to methods described in Appendix 3.5. Both leaf and root samples were dried according to the procedures described in Appendix 3.5 and are reported as such. In addition, soil from each pot was sampled. Soil, leaf and root analysis followed the same analytical procedures as described in Appendix 3.5. Roots were weighed and root length and girth were measured with a steel tape and a 150 mm digital vernier (0.01 mm metric) (Lutron DC515 ®), respectively.

7.2.4 Statistics

The results were submitted to analyses of variance (ANOVA) as explained in Section 3.2.3.5.

7.3 Results and discussion

7.3.1 Soil analysis

The particle size distributions of the soils used are given in Table 7.2 and their chemical properties and clay mineralogy in Table 7.3. The soils in the uThukela valley (Sun Valley, Nkaseni and Bloukrans) have a silt fraction ranging between 25.8 and 28% as compared to the Ruigtefontein and DARS silt fractions of 2.9 and 10.1%, respectively. The sandstone of the Vryheid Formation, Ecca Group (Land Type Survey Staff, 1986a) of the Utrecht / Dundee area has resulted in the latter two soils having 95.7 and 80.4% sand, respectively, while that of the other three soils ranged from 22.8 to 45.3%, probably as a result of the surrounding shale of this part of the uThukela drainage basin (Land Type Survey Staff, 1986b).

All the soils except that from DARS had a $\text{pH}(\text{KCl}) > 5.5$. The three soils from the uThukela drainage basin had high total cations ranging between 22.85 and 29.91 $\text{cmol}_c \text{L}^{-1}$. These soils are regarded as eutrophic (Soil Classification Working Group, 1991) with high values of Ca and Mg that are much greater than those found at DARS and Ruigtefontein. Exchangeable K

levels in the three former soils are also much higher than the Ruigtefontein and DARS samples, due probably to the influence of their greater clay contents and their clay mineralogy. Organic carbon percentages were generally low in all the soils due to the prevailing environmental conditions.

The soils from the Nkaseni area contained 2:1 clay minerals (smectite (Nkaseni); a mixed-layer smectite/vermiculite/illite with discrete kaolinite (Bloukrans), and illite with sub-dominant kaolinite (Sun Valley)). The soil from near Utrecht (Ruijgfontein) was kaolinitic in the (very low) clay fraction and the soil from DARS was the one used for the field experiments (Chapters 3, 4, 5 and 6) and consisted of kaolinite with sub-dominant illite in the clay fraction (Table 7.3).

Table 7.2: Particle size distribution of the five soils (0-30 cm depth)

Soil	Clay (<0.002 mm)	Fine silt (0.02-0.002 mm)	Coarse silt (0.05-0.02 mm)	Very fine sand (0.1-0.05 mm)	Fine sand (0.25-0.1 mm)	Medium sand (0.5-0.25 mm)	Coarse sand (2.0-0.5 mm)	Textural class
DARS	9.5	7.2	2.9	14.1	22.6	26.4	17.3	Loamy sand
Ruigtefontein	3.3	1.0	1.0	1.9	9.8	40.7	42.3	Pure sand
Bloukrans	49.2	11.1	16.9	2.2	2.7	7.8	10.1	Clay
Nkaseni	36.4	9.6	16.2	10.2	8.2	10.8	8.6	Clay loam
Sun Valley	27.8	14.3	12.6	4.6	6.3	15.4	19.0	Sandy clay loam

Table 7.3: Chemical analysis of the five soils (0-30 cm depth) prior to chicory planting and their clay mineralogy

Soil	Sample density (g mL ⁻¹)	pH (KCl)	Acid sat. (%)	Exch. acidity (cmol _c L ⁻¹)	Total cations (cmol _c L ⁻¹)	P (mg L ⁻¹)	K (mg L ⁻¹)	Ca (mg L ⁻¹)	Mg (mg L ⁻¹)	Organic carbon (%)	Clay mineralogy
DARS	1.35	4.5	9	0.35	3.89	112	54	622	37	0.8	Kaolinite/illite
Ruigtefontein	1.58	7.3	2	0.04	1.77	2	23	265	42	<0.5	Kaolinite
Bloukrans	1.00	7.2	0	0.10	27.61	75	332	3676	1010	<0.5	Mixed-layer
Nkaseni	1.04	5.9	0	0.14	29.91	60	315	4501	790	<0.5	Smectite
Sun Valley	1.08	6.0	0	0.10	22.85	300	392	3138	740	1.4	Illite

7.3.2 Yield

Wet root mass did not show a significant relationship with applied K although there was a highly significant positive relationship with clay percentage ($p < 0.001$) (Appendix 7.5). In the field trial (Chapter 4) this lack of root mass response to applied K was also found. The Nkaseni soil predominately comprising smectite in the clay fraction significantly outperformed the other samples (Table 7.4).

Wet leaf mass was highly significantly correlated with clay content ($p < 0.001$) and applied K ($p = 0.014$), with the Nkaseni soil again outperforming the others (Table 7.4). Root length and clay content were highly significantly positively correlated ($p < 0.001$) with the Ruigtefontein soil significantly different from the others probably as a consequence of its lower clay percentage. Löfkvist et al. (2005) reported on the ability of chicory roots to modify subsoil structure and act as a biological method (Brunetti, 2003) to aerate the subsoil. Root chicory's ability to penetrate compacted soils (Gentile, 2003) has been established in soil cropping systems in Uruguay. Root girth and clay content also gave a highly significant correlation ($p < 0.001$). However, in this instance the Bloukrans soil performed the poorest and the Nkaseni soil the best.

Table 7.4: Mean (n=3) characteristics of root chicory yields in the five soils

Soil	Leaf mass wet (g)	Root length (cm)	Root mass wet (g)	Root girth (mm)
DARS	96.9	18.9	182.5	30.0
Ruigtefontein	74.5	23.5	169.8	24.8
Bloukrans	111.6	18.3	207.5	23.4
Nkaseni	137.0	20.0	275.8	32.7
Sun Valley	102.3	20.8	202.2	28.9
CV%	23.6	15.4	25.8	24.3
l.s.d.	16.5	2.1	35.7	4.5
S.E.M.	24.7	3.1	53.5	6.8

7.3.3 Soil

7.3.3.1 Potassium behaviour over time

The amounts of K in the control (K0) pots of the five soils both after three harvests of soybeans in four of the soils and after chicory harvest are given in Table 7.5. After soybean, exchangeable K did not decline significantly in the Nkaseni or Bloukrans soils, but did decrease significantly in the DARS and Sun Valley soils. The control treatments showed an increasing amount of K used according to clay amount and perhaps clay type. The largest decrease in exchangeable soil K after the chicory harvest (118 mg K L⁻¹) was in the Bloukrans soil (49.2% clay; mixed-layer clay mineralogy) (Table 7.5).

Prior to the start of the pot trial the exchangeable K in the soils ranged from 23 to 391 mg L⁻¹, indicating that the soils were very low to moderate (Manson et al., 2012) in K availability. After harvesting of chicory the soils ranged from 16 to 199 mg L⁻¹; a significant (p<0.05) (Appendix 7.6) decrease in exchangeable K (Table 7.5).

Table 7.5: Utilisation of exchangeable soil potassium (K) from initial analysis to final harvest of chicory for five soils from the control (K0) pots

Soil	Initial K (mg L ⁻¹)	After soybean K (mg L ⁻¹)	In-S ¹ K (mg L ⁻¹)	After chicory K (mg L ⁻¹)	S-Ch ² K [#] (mg L ⁻¹)
DARS	142	54	88	51	3
Ruigtefontein	23	na*	na	16	7
Bloukrans	332	309	23	191	118
Nkaseni	315	251	64	183	68
Sun Valley	391	238	153	199	39

[#]CV% 40.1; l.s.d. 54.43; S.E.M. 74.47 at p<0.05

¹ In-S: Initial – Soybean

² S-Ch: Soybean-Chicory

* na: not applicable

Wood and Meyer (1986) suggested a critical exchangeable K level for sugarcane of 150 mg kg⁻¹ for soils with clay contents between 30 and 40% and 225 mg kg⁻¹ for soils with >40% clay. Manson et al. (2012) suggested 120 mg K L⁻¹ (sample density <1.35 g mL⁻¹) for maize, a crop calibrated under KZN conditions. The variability in K recommendations is typical of different crop requirements. The kaolinite and the kaolinite/illite dominated soils (both of

which are very low in clay) proved to be the lowest in exchangeable K after harvesting chicory at 16.3 and 50.7 mg L⁻¹, respectively (Table 7.5), and can be regarded as being low to very low in exchangeable K (Wood and Meyer, 1986; Manson et al., 2012). Initially these two soils were 23 and 54 mg K L⁻¹, respectively, indicating the small amount of exchangeable K (29.1% and 6.1%, equivalent to approximately 16.75 and 8.25 kg K ha⁻¹, respectively) removed by the chicory (Johnston et al., 1999). The medium clay (27%) Sun Valley and higher clay (36 and 49%) Nkaseni and Bloukrans soils, respectively, proved to be adequate in K prior to chicory planting but at harvest the two higher clay soils were depleted below the 225 mg kg⁻¹ threshold of Wood and Meyer (1986). The removal of K by chicory on the higher clay Nkaseni and Bloukrans soils was 68.3 and 117.7 mg K L⁻¹, respectively (27.2 and 38.1% difference) (Table 7.5), equivalent to 170.75 and 294.25 kg K ha⁻¹, respectively. Despite this large range in exchangeable K removal from the K0 soils (8.25 to 294.25 kg K ha⁻¹) the chicory plants did not show a significant difference in yield to applied K (Table 7.4). However, there was a significant difference between the various clay types. The three clay types progressively provided more exchangeable K depending on clay percentage in the order illite > smectite > mixed-layer. However, the smectitic soil (36% clay) produced a significantly higher yield with 170.75 kg ha⁻¹ exchangeable K utilised (Figure 7.2).

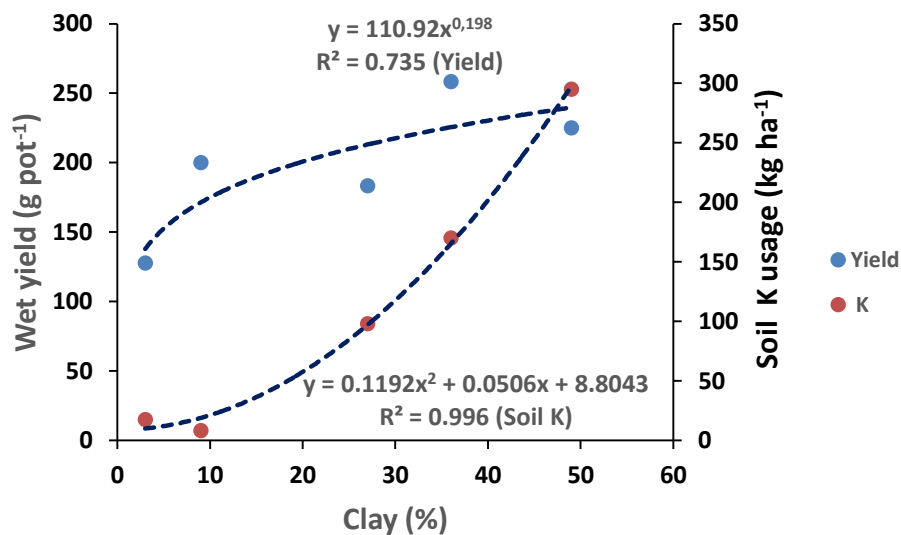


Figure 7.2: Mean wet yield (n=3) of root chicory and the equivalent soil potassium (K) usage of chicory on five soils with different clay percentages from control pots (Yield: CV% 25.8, l.s.d. 35.72, S.E.M. 53.54 at p<0.05).

It is apparent (Table 7.5) that root chicory was able to extract considerable amounts of exchangeable soil K but that it was used more as luxury uptake than to increase root yields.

The amount of exchangeable K removed was extrapolated from the K0 data (Table 7.6). On soils with 2:1 clay types, chicory removed the equivalent of 138 to 242 kg K ha⁻¹ whereas on the kaolinitic soils, removal ranged from 33 to 83 kg K ha⁻¹. The removal of K could have been greater from the Ruigtefontein and DARS soils if higher initial soil exchangeable K had been available due to chicory's innate ability for luxury uptake. The exchangeable K remaining after harvest was highest in the Bloukrans (mixed-layer clay) soil with a large amount of K (compared to the other soils) coming in an exchangeable form probably indicative of this soil's high buffer capacity (to be discussed in Section 7.3.2.3). The plants did not only use K from the exchangeable pool but also from the non-exchangeable or reserve K pool (Table 7.7) which will be discussed in Section 7.3.2.2. The Bloukrans soil was the only soil in which the crop did not have to draw on these K reserves.

Table 7.6: Mean total potassium (K) removed in dry matter (DM) for an assumed chicory population¹ using DM data from the control pots²

Soil	DM root yield (g pot ⁻¹)	DM leaf yield (g pot ⁻¹)	DM total plant K removed (%)	DM total yield (t ha ⁻¹)	Total K removed (kg ha ⁻¹)
DARS	50.9	12.89	1.04	8.0	83
Ruigtefontein	32.6	8.29	0.65	5.11	33
Bloukrans	57.3	19.52	1.67	9.60	160
Nkaseni	65.7	19.11	2.28	10.60	242
Sun Valley	46.6	15.19	1.79	7.72	138

¹ Assumed plant population = 250 000 plants ha⁻¹, ² See Appendix 7.7

Table 7.7: Soil potassium (K) removed by chicory plants, proportioned between exchangeable soil K and non-exchangeable K for control pots

Soil	Total K removed by plants* (kg ha ⁻¹)	Exchangeable K remaining in soil (kg ha ⁻¹)	Non-exchangeable K utilised (kg ha ⁻¹)
DARS	83	8	72
Ruigtefontein	33	18	15
Bloukrans	160	295	-
Nkaseni	242	170	74
Sun Valley	138	98	40

* 2.5 kg K to raise soil K by 1 mg L⁻¹ (Johnston et al., 1999)

7.3.3.2 Reserve potassium

Most soil analytical laboratories determine exchangeable K as a measure of the amount of plant-available K in the soil and do not determine the reserve K potential. Fertiliser K recommendations are thus often based only on exchangeable K which gives reasonable results in many soils and situations (Slaton et al., 2010; Rayment, 2013; Zörb et al., 2014; Bar-Yosef et al., 2015).

However, it has been established that soils containing especially micaceous or vermiculitic clays can release some non-exchangeable ('fixed') K when the exchangeable and solution K pools are depleted (O'Geen et al., 2008; Pettygrove, 2011). The DARS soil (kaolinite/illite) is an example where the final soil exchangeable K of 55.7 mg L^{-1} still provided a root yield that was significantly above the Ruigtefontein pure kaolinite clay type. It is likely that the illite present in the clay fraction provided the K from the non-exchangeable pool. Likewise, the illitic and smectitic clay types provided more K than was determined by the exchangeable extraction method. Hinsinger (2002) found that on some soils the K in the interlayer sites of clay minerals could make a considerable contribution (80-100%) to the K available to plants.

In earlier work, Rausel-Colom et al. (1964) and Scott and Smith (1966) reported that the release of non-exchangeable K from layer silicates occurs when the K concentration of the mineral environment is below a minimum level characteristic of each layer silicate. The release of this 'fixed' K is controlled by the ability of the growing plant to preserve the concentration in soil solution below this minimum. It was assumed that non-exchangeable K was only utilised when exchangeable K was limiting (Gothing, 1962; Beckett, 1964; Beckett and Nafady, 1967). However, Mackay and Russell (1975) refuted this and suggested that some plants may take up non-exchangeable K in the early stage of plant development, even when sufficient reserves of exchangeable K exist.

There are indications from Mengel and Kirby (2012) that earlier research (Fergus and Martin, 1974) indicated a difference in a plants' ability to exploit the interlayer sites for K. It is apparent that grasses and cereals are more effective than dicotyledonous plants and could account for the higher root length density of the grasses. Rengel and Damon (2008) have concluded that the utilisation of non-exchangeable K is a long-term process dependent on genotype. Root chicory showed its ability to utilise reserve K if one considers the amount extracted even from an initially low (23 mg K L^{-1}) kaolinitic, sandy soil, as well as the

amount from the 2:1 clay soils (Table 7.7). Steingrobe and Claassen (2000) working with sugar beet, wheat and potatoes found the former to be more efficient than the latter two in utilising non-exchangeable K. Trehan and Sharma (2002) and Trehan et al. (2005) differentiated between K-inefficient potato cultivars and efficient ones that seem to bring about chemical mobilisation of non-exchangeable K and surmised that this was as a result of secreted root exudates. However, Springob and Richter (1998) found a critical level of 4 μM in the rhizosphere solution below which the release of K from non-exchangeable pools was triggered.

Quantification of interlayer K dynamics is of importance in understanding the soil K cycle and critical for modeling K acquisition by crops on soils containing, especially, 2:1 clay minerals and would assist in the prediction of long-term K release capacity for field balance calculations (Öborn et al., 2005). Furthermore, the use of crops able to extract the non-exchangeable K fraction could be helpful as a green manure in crop rotation systems (Öborn et al., 2005).

The equilibrium reactions between the various K pools are of great practical importance as the amount of 'fixed' or non-exchangeable K can be relatively large. This non-exchangeable K from the smectite, illite and mixed-layer clays of the trial soils continually released K in amounts that are of practical importance. Early work by Evans and Attoe (1948) and Hoover et al. (1948) working with white clover (*Trifolium repens* L.) and pearl millet (*Pennisetum glaucum* L.), respectively, found that on some soil types up to 80% of the K came from the non-exchangeable forms for clover and up to 47% for the millet. Richards et al. (1988) found that maize from three long-term monoculture field trials, which did not receive applied K, extracted 24-35 kg non-exchangeable K $\text{ha}^{-1} \text{yr}^{-1}$. More recently, Miles and Farina (2014) established from extensive work in southern Africa on maize and sugarcane, over a number of years, that non-exchangeable K has the ability to supply a crop's K requirement from some soil types with little applied K. This work supports the findings of many other researchers internationally (e.g. Richards et al., 1988; Wood et al., 2003; Rayment, 2013).

This has led to the dilemma of testing for 'available' K on soils that have a high proportion of non-exchangeable K (Khan et al., 2014). The importance of 'fixed' K has been underestimated and Römheld and Kirby (2010) have put two possible reasons forward for this. Firstly, exchangeable K is easily measured in routine laboratory practice but established practice for non-exchangeable K is wanting. Secondly, the mechanism(s) of K release from

interlayer sites is not fully understood. As long as cognisance is taken of this, tests based on non-exchangeable K can lead to an improvement in the prediction of plant K availability (Dobermann et al., 1996; Mengel and Dou, 1998; Cox et al., 1999; Syers, 2003; Moody and Bell 2006; Prasad, 2009).

The effect of different clay types and their K reserve has been studied by a number of researchers (Wentworth and Rossi, 1972; Syers, 2003, Prasad, 2009; Römheld and Kirkby, 2010; Miles and Farina, 2014). Determining the slowly-available K reserve has been reported by a number of Australian researchers working on sugarcane (Haysom, 1971; Chapman et al., 1995; Schroeder and Wood, 2002; Schroeder et al., 2007) where K reserves were determined by boiling for 30 minutes with 1N HNO₃ and is reported as “nitric K”. This method, however, is not common practice for soil laboratories to perform as it is too laborious for routine use; although a new, quicker modification by Lee-Steere et al. (2014) using microwave heating has been proposed. Although several researchers (e.g. Metson, 1968; Quémener, 1979; Richards and Bates, 1988) have shown that increasing the number of extractions with nitric acid produced ever-declining amounts of K, it has been widely accepted that a 30-minute boiling period is sufficient to extract a meaningful amount of K, in terms of crop response, from the soil sample.

The amounts of total K in the soils with 2:1 clays are significantly different from those with 1:1 clays. Interestingly the Ruigtefontein soil has a higher total K than that from DARS (Table 7.8) according to the XRF data. This is probably due to the parent material (sandstone) and the subsequent degree of weathering of the parent material. The importance of K release from soil feldspars cannot be ignored. A number of researchers have described trials that show a significant lack of response by crops such as maize (*Zea mays* L.) to K applications on sandy soils (Liebhardt et al., 1976; Sparks et al., 1980; Woodruff and Parks, 1980; Parker et al., 1989b) of the Atlantic Coastal Plain Region of the USA. The lack of crop response is uncharacteristic, since these sandy soils have low levels of solution, exchangeable, and non-exchangeable K (Sparks, 1987; Parker et al., 1989a) similar to the Ruigtefontein sample. However, they often contain large quantities of mineral K, particularly as feldspars, and this is thought to result in the lack of plant response to applied K.

The illitic and mixed-layer clay soils are higher in K as these have a higher fixing capacity for K than smectite; this is because the major source of negative charge is in the silica

(tetrahedral) sheet (Weil and Brady, 2016). The comparison between the total K results by XRF (Table 7.8) and that extracted by the nitric K method is illustrated in Figure 7.3.

Table 7.8: Total potassium (K) measured by X-ray fluorescence spectrometry in the five soils prior to experimentation

Soil	Clay mineralogy	K (cmol _c kg ⁻¹)
DARS	Kaolinite/illite	12.67
Ruigterfontein	Kaolinite	19.53
Bloukrans	Mixed-layer	46.01
Nkaseni	Smectite	32.38
Sun Valley	Illite	61.16

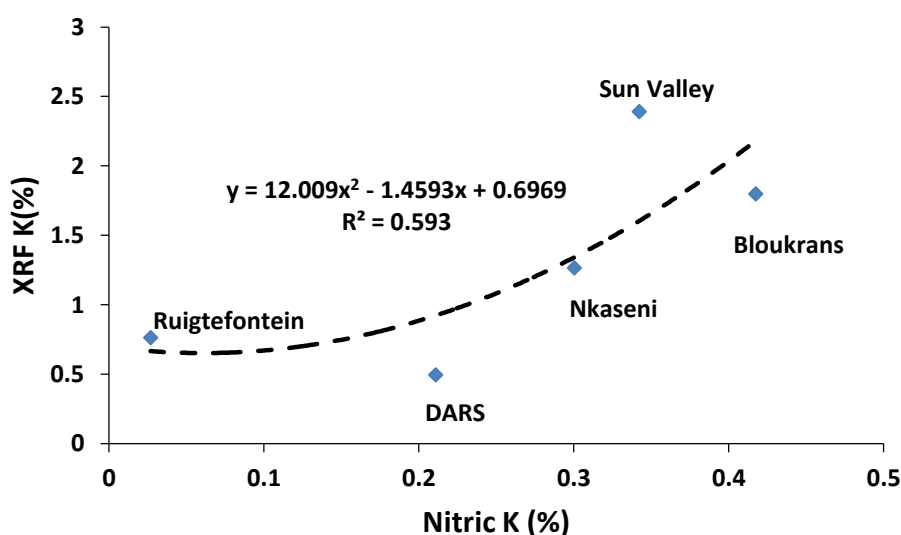


Figure 7.3: Comparison of potassium (K) determined by X-ray fluorescence (XRF) spectrometry and nitric potassium (K) acid extraction for the initial soil samples.

Table 7.9 gives the nitric K results from the control pots initially (excluding the Ruigterfontein sample as it had a very low K level at the outset) and after chicory harvest and the decrease in extracted K in all the soils is evident. Translating the results into percentages (Table 7.10) illustrates how the DARS and Bloukrans soils initially had relatively low exchangeable K in relation to the non-exchangeable K. This proportion increased markedly after cropping as the percentage of non-exchangeable K decreased. In contrast, the Nkaseni and Sun Valley soils remained fairly constant in their proportions of exchangeable and non-exchangeable K.

Table 7.9: Initial and final nitric potassium (K), non-exchangeable and exchangeable K for the five soils from the control pots

Soil	Initial nitric K ($\text{cmol}_c \text{ kg}^{-1}$)	Initial exch.K ($\text{cmol}_c \text{ kg}^{-1}$)	Initial non- exch. K ($\text{cmol}_c \text{ kg}^{-1}$)	Final nitric K ($\text{cmol}_c \text{ kg}^{-1}$)	Final exch K ($\text{cmol}_c \text{ kg}^{-1}$)	Final non- exch. K ($\text{cmol}_c \text{ kg}^{-1}$)	Non-exch. K used ($\text{cmol}_c \text{ kg}^{-1}$)
DARS	5.39	0.36	5.03	0.86	0.14	0.72	4.31
Ruigterfontein ¹	0.69	0.06	0.63	0.46	0.04	0.59	0.04
Bloukrans	10.67	1.08	9.59	6.50	0.85	5.65	3.94
Nkaseni	7.68	1.06	6.62	5.04	0.81	4.23	2.39
Sun Valley	8.75	1.33	7.42	6.26	1.00	5.26	2.16

¹ one harvest only; other soils four harvests (three soybean and one chicory)

Table 7.10: Exchangeable and non-exchangeable potassium (K) expressed as a percentage of nitric K for the five soils from the control pots initially and after chicory

Soil	Exchangeable K (initial) (%)	Non- exchangeable K (initial) (%)	Exchangeable K (final) (%)	Non- exchangeable K (final) (%)
DARS	7	93	16	84
Ruigterfontein	9	91	9	91
Bloukrans	10	90	13	87
Nkaseni	14	86	16	84
Sun Valley	15	85	16	84

That K was released from non-exchangeable sources is indicated by the small to moderate decrease in exchangeable K, in comparison to the removal of K by the plants, especially from the Sun Valley and Nkaseni soils. It has been established (Verma, 1963; Scott and Smith, 1966; Wentworth, 1969) that 2:1 layer silicates are the main sources of such non-exchangeable K.

It is suggested that the K requirements of chicory could be supplied by this reserve. Miles and Farina (2014), in a study of 429 sugarcane topsoils from South Africa, Zimbabwe, Zambia, Malawi and Tanzania, found a wide range of non-exchangeable (nitric) K from 0 to 17.9 $\text{cmol}_c \text{ kg}^{-1}$. Nitric K is considered to represent the soil supplying power of K for long term cropping (Schroeder et al., 2007; Miles and Farina, 2014). Australian work on sugarcane (Schroeder et al., 2007) seems to suggest that nitric K values of greater than 2.5 $\text{cmol}_c \text{ L}^{-1}$ are sufficient and no fertiliser K is then required. The pot trial results illustrate that initially only the Ruigterfontein sample was below this threshold, while even after four harvests (three

soybeans and one root chicory), the Bloukrans, Nkaseni and Sun Valley soils were still well above this amount. Chapman (1971) was of the opinion that the nitric K correlated more closely with the response to K fertiliser than the exchangeable value.

In both the field trial (Chapter 4) and the pot trial, applied K was non-significant with regard to yield of root chicory, especially on soils with an appreciable non-exchangeable K reserve. This was true even for the Ruigtefontein soil that had very low initial exchangeable K.

The results of the pot trial indicated a significant role for clay type and led to a further investigation into the absorption/desorption of K on these soils using K sorption isotherms.

7.3.3.3 Potassium adsorption isotherms

The adsorption isotherm technique can be used to make K fertiliser recommendations based on knowledge of equilibrium with the amount of a substance in soil solution and the quantity that is adsorbed by the solid phase of the soil (Sparks and Huang, 1985). This relationship implies that the ability of a soil system to maintain a certain concentration of a cation in solution is determined by the total amount of the cation present in readily available forms (exchangeable and soluble) and the intensity by which it is released into the soil solution (Le Roux and Sumner, 1968). The advantage of sorption techniques is the relatively short laboratory time required to produce a sorption curve that can be used for fertiliser recommendations (Solis and Torrent, 1989). The sorption isotherms were measured on soils prior to the pot trial and after the harvesting of chicory; these latter samples were taken from control pots that had not received K.

The amount of K sorbed (cmol K kg^{-1}) was plotted against the equilibrium solution concentration (mmol K L^{-1} in 1 mmol CaCl_2) to produce isotherms indicative of a progressive reduction in the amount of K sorbed for each increment in concentration of K in solution. The data are discussed in relation to the Freundlich adsorption model only, as it was found that the Temkin model (Appendix 7.8) gave very similar results to the Freundlich. The Langmuir model (Appendix 7.8) was not as good for the pre-trial samples as the Temkin and Freundlich and was found to be much worse for the post-harvest samples, probably as a result of the mixed mineralogy of the soils (Pal et al., 1999), and so was not considered further. Hannan et al. (2007) also found that the Langmuir equation did not explain their K adsorption data in Pakistan as well as the Freundlich model.

Freundlich model

This model, developed by Freundlich (1906) and derived mathematically by Sposito (1980), assumes that adsorption occurs on a heterogeneous surface with adsorption energy that is non-uniformly distributed and decreases logarithmically with an increased coverage allowing the parameters of the equation to be compared among soils.

The log transformed data fitted well for four of the five soils to the Freundlich equation for both pre-trial and post-harvest samples (Table 7.11). The Ruigtefontein sample was the exception and the poor fit to the data cannot be explained although the very low clay percentage (3%) could have contributed in some way to this result. Shayan and Davey (1978) considered the 'a' constant (the intercept, reflecting the extent of adsorption) to be a capability factor indicating that the higher the value the greater a soil's adsorption capacity. Assimakopoulos et al. (1986) stated that the 'a' value of the Freundlich model represents the quantity of adsorbed K required to maintain K concentration in the solution at one unit (e.g. 1 mg K L⁻¹). Consequently, soils with a large portion of their adsorption sites occupied would retain less K from the soil solution in order to maintain its concentration at 1 unit.

Higher values of the 'b' constant (the slope of the isotherm, reflecting the energy of adsorption) indicate that a relatively small change in the solution K concentration will cause a relatively large change in K adsorbed. If K remained tightly bonded on the adsorption sites, then a soil already with a large portion of its adsorption sites occupied would tend to produce a less steep slope in the log plot of x/m versus C (Assimakopoulos et al., 1986). Bhal and Toor (2002) stated that the 'b' value of the Freundlich model indicates the rate of adsorption of K, and a decline in value would indicate a reduction in K adsorption.

Table 7.11: Freundlich adsorption isotherm equations for the five soils from the control pots before planting and after harvest

Soil	Dominant clay	Equations (initial)	R² (initial)	Equations (final)	R² (final)
DARS	Kaolinite/illite	Freundlich: $y = 1.0979x + 0.4382$	0.978	Freundlich: $y = 0.5679x + 0.7096$	0.903
Ruigtefontein	Kaolinite	Freundlich: $y = 0.0828x + 1.2225$	0.004	Freundlich: $y = 0.0828x + 1.2225$	0.004
Bloukrans	Mixed-layer	Freundlich: $y = 1.1131x + 0.6749$	0.984	Freundlich: $y = 0.7492x + 1.6978$	0.995
Nkaseni	Smectite	Freundlich: $y = 0.8098x + 1.8394$	0.984	Freundlich: $y = 0.7352x + 1.2903$	0.981
Sun Valley	Illite	Freundlich: $y = 0.8941x + 1.0126$	0.994	Freundlich: $y = 0.7692x + 1.087$	0.999

The results of the initial sampling before the pot trial showed that the soils containing kaolinite/illite and the mixed-layer clay were significantly higher in their adsorption capacity than the illitic and smectitic soils indicating that the amount of K ready for release to the plants was higher from the former clay types than the latter (Table 7.12). Post-harvest 'a' values were low suggesting that part of the exchangeable K was held on exchange sites with high bonding energy. The DARS and Ruigtefontein 'a' values were particularly low, while the soils containing more 2:1 clay were also lower than the initial values, but very similar to each other, indicating a lower amount of K ready for release (Applied 7.9).

Table 7.12: Freundlich 'a' and 'b' constants before the pot trial and after harvest in the control potassium (K) treatments of the five soils

Soil	Clay mineralogy	Adsorption capacity constant 'a' (before) (mg kg ⁻¹)	Adsorption capacity constant 'a' (after) (mg kg ⁻¹)	Adsorption intensity constant 'b' (before) (mg kg ⁻¹)	Adsorption intensity constant 'b' (after) (mg kg ⁻¹)
DARS	Kaolinite/illite	12.53	3.70	2.74	5.12
Ruigtefontein	Kaolinite	1.21	1.21	16.69	16.69
Bloukrans	Mixed-layer	12.98	5.61	4.73	49.97
Nkaseni	Smectite	6.45	5.44	69.09	19.51
Sun Valley	Illite	7.83	5.88	10.29	12.22

The K buffering capacity (KBC) of the soil is calculated from the amounts of K in soil solution (intensity factor) and the portion of K in the solid phase (quantity factor) in equilibrium with the K in solution. The buffering capacity is calculated from the K adsorption isotherm and it indicates the ability of soil to resist change in solution K. The KBC is obtained from the slope ('b') of the sorption isotherms (Beckett, 1964; Le Roux and Sumner, 1968). The pre-trial sampling gave a very high buffering capacity for the Nkaseni soil, followed distantly by the Sun Valley soil. The DARS and Ruigtefontein soils had much lower KBC. High values of buffering capacity are indicative of adequate K availability for long periods, while low values indicate a need for frequent fertilisation (Koch et al., 1970; Sparks and Liebhardt, 1981; Sharpley, 1990). After harvest there was a change in KBC values with the kaolinite/illite, smectite, and mixed-layer clay soils showing significant differences ($p < 0.05$) from the "before" result. The smectitic soil (Nkaseni), however, decreased significantly while the others increased (Table 7.12); the decline in 'b' value indicating a reduction of the energy of adsorption from its pre-trial level.

The Freundlich model proved to be reliable for all samples (except the Ruigtefontein soil which was expected due to its very low clay content and 1:1 clay type) with R^2 values >0.90 (Table 7.11). Furthermore, it is reported that over a limited range of concentration, the Freundlich equation often describes K adsorption well (Barrow, 1987; Sidhu et al., 2004). However, it should be appreciated that the good fit of the data to the Freundlich adsorption isotherm equation is partially due to the insensitivity of the linear form as it is a log-log plot (Goldberg et al., 2005).

Use of this model provided a method for field K fertilisation rates to be calculated (Table 7.13) according to the formulae given in Section 7.2.2.2 for various target levels of soil solution K (0, 6, 12, 18, 24, and 27 mg L⁻¹). The initial adsorption equilibrium solution K concentration serves as an index of K availability.

The initial exchangeable K in the DARS soil was 142 mg L⁻¹ in the topsoil (Table 7.13) and according to Manson et al. (2012) would be adequate and no K would be required for a number of row crops (maize, soybeans, wheat, groundnut and drybean). However, the soil's clay mineralogy and the subsequent K isotherm values suggest that additional applied K would be required to satisfy the target concentration of K in the soil solution than indicated by the exchangeable value.

The Ruigtefontein soil was severely depleted of K; hence the low adsorption capacity (1.21 mg kg⁻¹). However, its KBC was relatively high in comparison to the DARS soil probably due to the surrounding sandstone geology as previously discussed (Section 7.3.2.2). Both the Nkaseni (smectite) and Sun Valley soils (illite) had a higher (to the Ruigtefontein sample) but similar adsorption capacity and therefore similar fertiliser recommendations. However, the Nkaseni soil had a much greater adsorption intensity reflecting the inherent reserve K capacity (Table 7.13) of this soil. The Bloukrans soil that contained mixed-layer clay, reacted similarly to the DARS soil with a strong adsorption capacity (12.98 mg kg⁻¹) and strong reaction to a target concentration of K in the soil solution up to 1 018 kg K ha⁻¹ at 27 mg L⁻¹. This soil also showed a slightly higher buffering capacity than the DARS soil.

Table 7.13: Initial calculated fertiliser requirements for the five soils based on different target concentrations of potassium (K) in solution.

Soil	Initial exchangeable soil K (mg L⁻¹)	Target conc. of K in soil solution (mg L⁻¹)	Initial quantity of K (mg kg⁻¹)	Initial quantity of K (kg ha⁻¹)
DARS	142	0	0	0
		6	90	179
		12	192	384
		18	299	599
		24	411	821
		27	467	934
Ruigtefontein	23	0	0	0
		6	1.4	2.8
		12	1.5	3
		18	1.5	3
		24	1.6	3.2
		27	1.6	3.2
Nkaseni	315	0	0	0
		6	28	55
		12	48	96
		18	67	134
		24	84	169
		27	93	186
Bloukrans	332	0	0	0
		6	95	191
		12	206	413
		18	324	648
		24	446	893
		27	509	1018
Sun Valley	391	0	0	0
		6	39	78
		12	72	144
		18	104	208
		24	134	268
		27	149	298

7.3.4 Plant

7.3.4.1 Leaf

Leaf sampling at 60, 120 and 180 DAS provided further insight into the uptake of K over time. The other trials (Chapters 3, 4, 5 and 6) were only evaluated at 60 DAS and at harvest for K in the leaf. The extra sampling at 120 DAS showed an increase in K uptake to this point

then a decrease towards harvest (Figure 7.4). Standard practice for chicory requires leaf sampling at 60 DAS (Hochmuth et al., 1991, 2009; Reuter and Robinson, 1997) so fertiliser corrections can be made. However, the 120 DAS results assist in providing an indication of the upward trend of K over time and could benefit landowners considering lowering high K levels in their soils by indicating when the plant nears maximum K uptake.

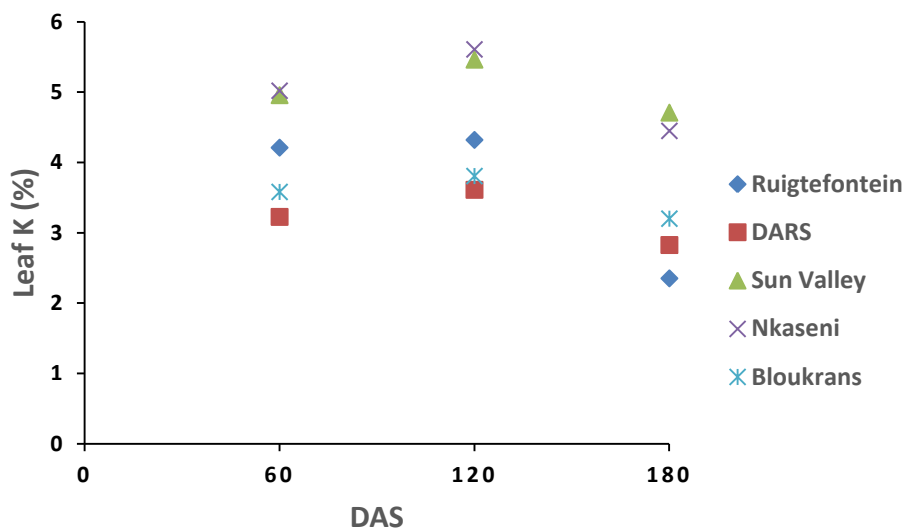


Figure 7.4: Leaf potassium (K) at 60, 120 and 180 days after sowing (DAS) for the five soils (n=3) (Leaf K% at (a) 60 DAS: CV% 13.8, l.s.d. 0.3874, S.E.M. 0.5806; at (b) 120 DAS: CV% 20.1, l.s.d. 0.6121, S.E.M. 0.9173; at (c) 180 DAS: CV% 19.4, l.s.d. 0.4545, S.E.M. 0.6812 all at $p < 0.05$).

The 60 DAS leaf sample gave a good interaction of leaf K percentage with soil type and possibly clay percentage and mineralogy (Figure 7.5 and Table 7.14). There was increasing K percentage in the leaf with the addition of applied K at all three sampling times (Figure 7.6). At 60 DAS the K percentage in the chicory leaves had a highly significant ($p < 0.001$) correlation with clay content, applied K and their interaction ($p = 0.007$) (Appendix 7.10). The Nkaseni and Sun Valley soils, both 2:1 dominant clay types, gave the highest mean leaf K percentage but their coefficient of determination was the lowest of the five soils (Table 7.14) with applied K. In contrast, three other soils (DARS, Ruigtefontein and Bloukrans) with higher percentages of kaolinite gave better R^2 values. The Ruigtefontein soil gave a progressive increase in leaf K percentage with each increment in applied K with an R^2 of 0.984. One possible explanation for this could be that applied K on this low clay, kaolinitic soil is subject to minimal K fixation and K is readily taken up by the plant and translocated to the leaf. The other explanation for the good interaction with applied K might be due to the

continual replenishment of decanted leaching water to the pots thus allowing K to be recirculated and not leached as natural conditions would have dictated in this low clay soil. The other soils have varying percentages of 2:1 clay types that could fix and release K at different rates and hence their lower coefficients of determination.

The interaction of soil with leaf K percentage at the two other sampling times (120 and 180 DAS) proved to be non-significant. Over time, first (at 120 DAS) the interaction of clay content with applied K became non-significant, and then at 180 DAS the applied K became only moderately significant with leaf K percentage while the clay content and applied K interaction was non-significant.

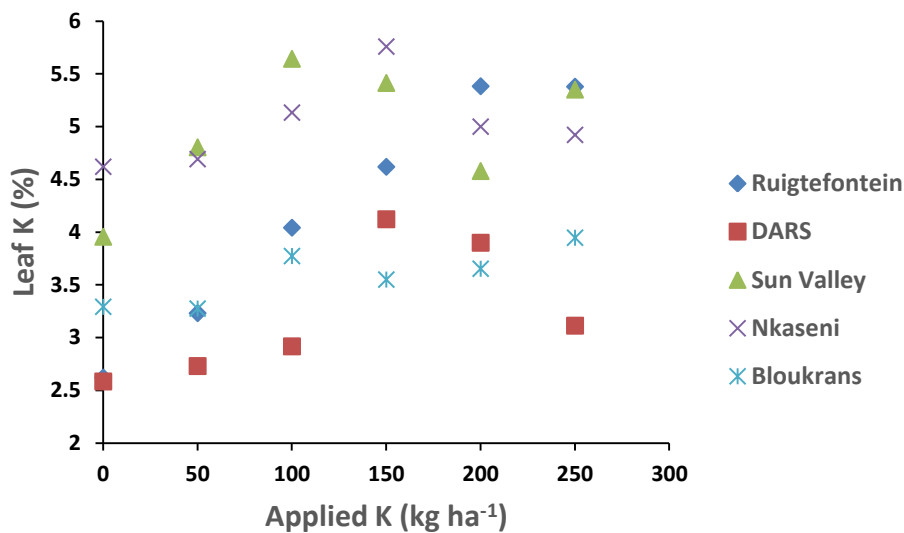


Figure 7.5: The interaction between leaf potassium (K) at 60 days after sowing (n=3) with different amounts of applied K on five different soils.

Table 7.14: Quadratic equations and coefficients of determination for the interaction between the means of leaf potassium (K%) at 60 days after sowing with applied K (kg ha⁻¹) on five different soils

Soil	Equation	R ²
DARS	$y = -4E-05x^2 + 0.0155x + 2.326$	0.616
Ruigtefontein	$y = -2E-05x^2 + 0.0177x + 2.5302$	0.984
Nkaseni	$y = -4E-05x^2 + 0.0177x + 4.4711$	0.598
Bloukrans	$y = -2E-07x^2 + 0.0024x + 3.2802$	0.707
Sun Valley	$y = -5E-05x^2 + 0.0161x + 4.102$	0.561

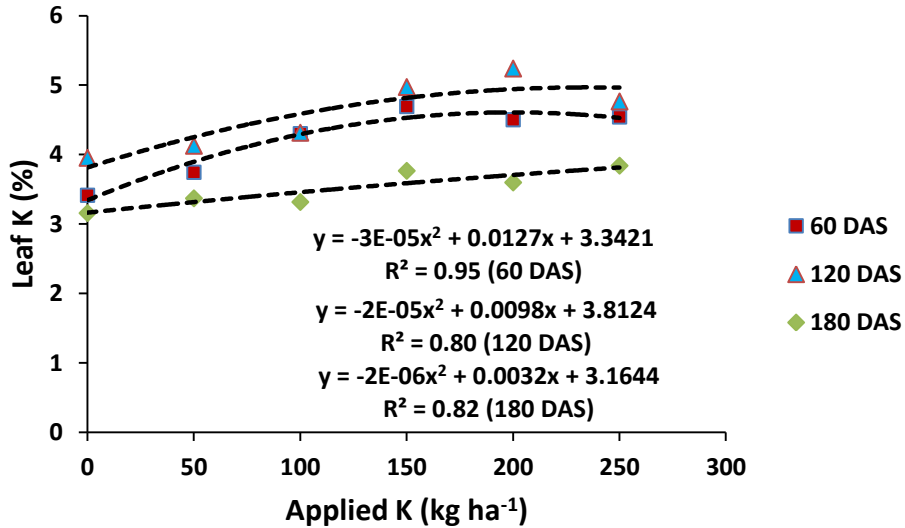


Figure 7.6: Leaf potassium (n=3) (K) at 60, 120 and 180 days after sowing (DAS) with different amounts of applied K across all five soils (Leaf K% at (a) 60 DAS: CV% 13.8, l.s.d. 0.4244, S.E.M. 0.5806; and (b) 120DAS: CV% 20.1, l.s.d. 0.6705, S.E.M. 0.9173; and (c) 180 DAS: CV% 19.4, l.s.d. 0.4979, S.E.M. 0.6812 all at p<0.05).

Due to its high rate of redistribution between mature and developing tissues mild K deficiency in crops is not immediately visible. Unlike with N and P no major change takes place in biomass partitioning or root formation after the onset of K deficiency and was probably the reason why it was difficult to ascertain K deficiency in the pot trial. Plants with leaf K of <2.9% started to show symptoms of K deficiency (brown, yellow flaring around the edges of the leaf, Plate 7.2). These seemed more prominent in the DARS soil than the Ruigtefontein soil despite the latter having the lower exchangeable K, possibly a result of adsorption by illite of the re-circulated K in the DARS soil.



Plate 7.2: Potassium deficiency (soil K=51 mg L⁻¹) when sampled at harvest; leaf K=2.43% when sampled at 60 days after sowing (DAS) from control pot of DARS soil photographed at 160 DAS.

7.3.4.2 Root

At harvest, the roots had K percentages that were highly significantly correlated ($p < 0.001$) with clay percentage (Appendix 7.11). The smectitic Nkaseni soil had the highest K percentage in the root (Table 7.15) followed by the illitic Sun Valley soil. These two samples have higher KBC's that are indicative of adequate K availability for long periods and are thus able to supply soil K to plant roots on a more sustained basis. Mengel (1980) showed that the critical K level in a soil was related to its KBC and that each soil would have its own critical K level. However, it was apparent in the pot trial that the percentage K in the roots was not related to the amount of applied K, although the interaction of applied K and clay content was moderately significant ($p = 0.055$).

The field trials reported in previous chapters were all done on a sandy loam soil at DARS. The root K levels recommended for optimum chicon production are 1.5-2.0% K (RTFA, 2015; Table 6.7). All roots from control pots, other than those of Sun Valley would have been inadequate with regard to K (Sarrazyn and Deckers, 1991) according to those norms (Table 7.15). The three samples from the uThukela drainage basin (Bloukrans, Nkaseni and Sun Valley) had greater root K than their kaolinite-dominated counterparts from the Dundee/Utrecht area; a reflection of their type of clay and reserve K.

Table 7.15 : Mean (n=3) root potassium (K) removal from the control pots of five soils

Soil	Clay mineralogy	Clay (%)	Root yield (DM*) (g)	Root K (% DM)	Root removal K (kg ha ⁻¹)	Root K% (DM*) at 0 (kg K ha ⁻¹)	Root K% (DM) at 250 (kg K ha ⁻¹)	Difference K (%)
DARS	Kaolinite/illite	9	50.94	0.67	56	0.988	1.090	0.102
Ruigtefontein	Kaolinite	3	32.60	0.38	13	0.870	1.016	0.146
Nkaseni	Smectite	36	65.71	1.24	198	1.405	1.422	0.017
Bloukrans	Mixed-layer	49	57.31	0.94	228	1.231	1.321	0.09
Sun Valley	Illite	27	46.61	0.96	133	1.532	1.302	-0.23

* DM - dry matter basis. Root: CV% 10.7, l.s.d. 0.0871, S.E.M. 0.1306 at p<0.05.

At the highest fertilisation rate of 250 kg K ha⁻¹ there were increases especially for the DARS and Ruigtefontein samples but the soils with 2:1 clays remained very similar or showed a decrease in K percentage (Sun Valley) from the control pot results (Table 7.15). However, all samples fertilised with 250 kg K ha⁻¹ still did not meet the criteria for the K% Dutch norms (RTFA, 2015). In a trial of this nature where the leachate was recirculated, it should have been conducive to full utilisation of K by the plants, yet the results were still below the Dutch norms. Potassium root levels were mainly below the 1.5 K% norm with only 10% of the total trial above the norm with the Nkaseni and Sun Valley soils performing the best with regard to root K levels.

Magnesium and Ca play an important role in K assimilation (Pujos and Morard, 1997; Tuma et al., 2004; Ujwalaranade-Malvi, 2011; Hawkesford et al., 2012). Calcium levels in the root were inadequate and only about 2% of the trial was found to meet the Dutch root norms (RTFA, 2015). Magnesium levels were better across the trial with 26% meeting these norms, 20% accounted for by 2:1 type clay soils. In this case unlike the field trials on the DARS which were on soils with inherent low Ca and Mg levels (Ca <650 mg L⁻¹; Mg <60 mg L⁻¹), the uThukela drainage basin soils are high in Ca and Mg (Ca 3 100-4 500 mg L⁻¹; Mg 700-1 100 mg L⁻¹) yet the root norms were still not met in the majority of roots sampled. This suggests that possibly environmental conditions (White and Broadley, 2003; Lecourieux et al., 2006; McAinsh and Pittman, 2009) play an overriding influence on the manner in which root chicory assimilates and responds physiologically to some of these elements (especially Ca). Given the yields obtained in the pot trial it appears that the root norms for these elements are probably lower for the hotter conditions in KZN than suggested by the Dutch researchers (Sarrazyn and Deckers, 1991) for K, Ca and Mg.

7.3.4.3 Soil, leaf and root potassium balance sheet

The utilisation of K by chicory for the various treatments (Table 7.16) indicates that the plants used a proportion of reserve K. The DARS soil's maximum K utilisation was at 250 kg ha⁻¹ with the major contribution, as with all the other soils, coming from the leaf, while the roots extracted the most at 200 kg K ha⁻¹. The relationship between the applied K and that used by the plant ($R^2 = 0.162$), was very weak suggests a contribution from the subdominant illite. The correlation improved ($R^2 = 0.926$) when the applied K was compared to final remaining exchangeable soil K, suggesting a positive contribution to exchangeable K from the applied K.

The Ruigtefontein soil gave the highest uptake of K at 200 kg K ha⁻¹ and the leaf withdrawal was also maximised at that application rate, however, maximum root K occurred at the lower level of 150 kg K ha⁻¹. A strong linear correlation ($R^2 = 0.883$) was found between the applied K and plant usage. The final exchangeable soil K was also well correlated with the applied soil K ($R^2 = 0.9804$) and is in all likelihood attributable to the nature of the clay type (kaolinite) with its low adsorption characteristics and the very low initial soil K status.

The Nkaseni (smectitic) sample gave a much higher K usage for both the root and the leaf at 150 and 250 kg K ha⁻¹, respectively, than the mainly kaolinitic samples, a possible consequence of the higher initial K levels both in exchangeable and non-exchangeable forms. However, the linear correlation between the applied K and that used by the plant was weak ($R^2 = 0.455$) suggesting a high cation adsorption capacity of the smectite attracting applied K cations with its large internal surface (Weil and Brady, 2016) between the crystal units. The linear correlation ($R^2 = 0.493$) between the applied K and final remaining exchangeable soil K was also weak.

The Bloukrans soil with its mixed-layer clay mineralogy showed maximum usage of K at 200 kg ha⁻¹ for both leaf and roots. The linear correlation between applied K and K usage by the plant was similar to the DARS soil ($R^2 = 0.174$). The final soil exchangeable K did correlate well with applied K ($R^2 = 0.871$) as the DARS soil suggesting a positive contribution to exchangeable K from the applied K.

The illitic Sun Valley soil continued to extract K to the highest K treatment level of 250 kg ha⁻¹ for both leaf and root. However, the linear correlation between the applied K and the

resultant plant usage was good ($R^2 = 0.710$) suggesting that the illitic requirement for K was satisfied at an early K treatment stage at a low application level of K. The final exchangeable soil K indicates an increase of exchangeable K at application rates greater than 50 kg K ha⁻¹ above the initial soil K level with a good correlation of $R^2 = 0.949$ and suggests an interplay between reserve and exchangeable K pools.

Table 7.16: Potassium (K) balance sheet for plants on five soils with six rates of applied K after one harvest of chicory

Sample Site	Initial soil K (kg K) ¹	Treatments (kg K ha ⁻¹)	Total plant K (%)	DM Root yield (kg ha ⁻¹)	DM Leaf yield (kg ha ⁻¹)	DM Root and leaf yield (kg ha ⁻¹)	Total plant K removed (kg ha ⁻¹)	Soil K remaining (kg ha ⁻¹)	Final soil K (kg K)
DARS	135	0	1.04	6 299	1 664	7 963	83	52	128
		50	1.18	5 876	1 655	7 531	136	49	192
		100	1.08	4 924	1 729	6 653	72	163	238
		150	1.34	5 295	2 060	7 355	99	186	160
		200	1.36	6 353	1 733	8 086	110	225	336
		250	1.53	5 981	2 105	8 630	132	253	320
Rfontein	58	0	0.65	4 075	1 017	5 092	33	25	41
		50	0.87	5 028	1 377	6 405	56	52	58
		100	1.10	5 083	1 590	6 673	73	85	62
		150	1.22	6 194	1 651	7 845	96	112	78
		200	1.33	6 171	1 580	7 751	103	155	78
		250	1.33	5 823	1 558	7 381	98	210	84
Nkaseni	628	0	2.29	8 204	2 440	10 644	244	384	458
		50	2.50	8 735	2 406	11 141	279	399	410
		100	2.27	7 464	2 557	10 021	271	457	595
		150	3.34	9 634	3 105	12 739	426	352	604
		200	2.80	8999	2 547	11 546	323	505	600
		250	2.79	9 529	3 195	12 724	355	523	948
Bloukrans	773	0	1.67	7 146	2 389	9 535	159	614	478
		50	1.29	5 295	2 224	7 519	97	726	870
		100	1.32	6 565	1 594	8 159	108	765	442
		150	1.71	6 299	2 330	8 629	148	775	618
		200	1.83	7 836	2 407	10 243	188	785	874
		250	1.73	6 406	2 232	8 638	149	874	879
Sun Valley	595	0	1.79	5 823	1 898	7 721	138	457	498
		50	1.79	6 724	1 758	8 481	152	493	588
		100	1.81	6 616	1 785	8 401	152	543	648
		150	1.86	5 876	2 133	8 009	149	596	983
		200	2.07	6 035	2 270	8 305	172	623	983
		250	2.27	7 464	2 275	9 696	220	625	680

¹(2.5 kg K to raise soil K by 1 mg L⁻¹ (Johnston et al., 1999))

7.4 Conclusion

7.4.1 Yield

The pot trial concurred with results in the field (Chapter 4) regarding the DARS, sandy loam soil, in that root chicory was unresponsive to applied K at the 5% level of significance, although it did show a positive trend. The crop did not react significantly even with very low exchangeable K values (23 mg L^{-1}) on the Ruigtefontein soil (3% clay). However, root chicory did respond significantly as a result of different clay contents and probably within them to the different clay minerals present. In particular, the soils containing illite (27% clay) and smectite (36% clay) gave significantly higher root and leaf yields ($p < 0.05$). Root length was positively related to texture, with the heavier soils having the greater length. Root girth was found to be greater in the smectitic Nkaseni soil than those from the other sites.

7.4.2 Soil

The soils consisted of a wide spectrum of textures ranging from 3 to 49% clay with both 1:1 and 2:1 layer silicates. Of the 2:1 clays the smectite (Nkaseni) proved to most strongly adsorb K (intensity of adsorption) followed by illite (Sun Valley) and the mixed-layer clay (Bloukrans). The soils containing dominant kaolinite did not show the same intensity of adsorption as the former clay types, but contained much less total clay. However, the DARS soil, with both kaolinite and illite in the clay fraction proved to have a relatively large adsorption capacity (quantity) due probably to its illite component. This was also true for the Bloukrans soil with its mixed-layer combination of illite, smectite, and vermiculite with discrete kaolinite. The K adsorption of the Nkaseni soil decreased over time with crop extraction of K, the Sun Valley illitic soil stayed constant while in the Bloukrans soil K adsorption increased with time. The DARS soil decreased over time.

The Freundlich adsorption isotherm provided a means to calculate fertiliser requirements for the different soil types based on their initial adsorption capacity. The DARS and Bloukrans soils indicated that the amount of K ready for release to the plants was higher from these clays types (kaolinite/illite and mixed-layer) but they had a large fertiliser requirement. As an example, there was a notable discrepancy in the initial DARS topsoil that had 142 mg L^{-1} exchangeable K and would be sufficient for a number of row crops. However, the soil's clay mineralogy and the subsequent K isotherm values suggested that additional applied K would

be required to satisfy the target concentration of K in the soil solution than indicated by the exchangeable value.

The 2:1 clay soils showed the greater resistance to change (greater buffer capacity) to added K. Potassium fixation was also more prevalent on these soil types whereby some of the applied K is relegated to the non-exchangeable pool to be used later in the exchangeable form when required by the plant.

Estimates of the non-exchangeable K from the soils established that all the soils had a K reserve that should be taken into account when soil fertiliser recommendations are made. Use of the nitric acid extraction method provided an estimate of the K reserve available in the different soils as a proportion of the total K determined by XRF analysis. The DARS and Bloukrans soils initially had relatively low exchangeable K in relation to the non-exchangeable K. This proportion increased markedly after cropping as the percentage of non-exchangeable K decreased. In contrast, the Nkaseni and Sun Valley soils remained fairly constant in their proportions of exchangeable and non-exchangeable K.

7.4.3 Leaf

Leaf analysis included an extra sampling at 120 DAS in addition to the 60 DAS and harvest sampling done previously (Chapters 3, 4, 5 and 6). It was apparent from this extra sampling that the uptake of K had an upward trend to this new sampling time and then declined towards harvesting, unlike previously where the 60 DAS sampling suggested a decline towards harvesting. Farmers who have lands high in K can use chicory to reduce K levels and maximise K removal at an optimal time of 120 DAS when leaf K values are at their highest.

Leaf K response to clay percentage (and perhaps clay mineralogy), and applied K was significant at the 60 DAS sampling; thereafter the influence of the applied K started to decline with the subsequent leaf samplings and became non-significant. Chicory has an innate ability to store nutrients in its leaf and K was no exception.

The Nkaseni and Sun Valley soils (2:1 dominant clay types) gave the highest mean leaf K percentage but had the lowest coefficient of determination of the five soils. In contrast the DARS, Ruigtefontein and Bloukrans soils with their higher kaolinite gave better R^2 values.

7.4.4 Root

In contrast to the field trial (DARS; sandy loam) (Chapter 4) the percentage of root K was not related to the amount of applied K, but the interaction of applied K and clay content was moderately significant ($p=0.055$) and possibly the higher the buffer capacity the greater the availability of K for longer periods to the root. It was evident that the clay percentage and type played a highly significant role on the amount of K in the root. The smectitic Nkaseni soil had the highest root K percentage over all K treatments followed by the illitic Sun Valley soil.

Root K levels did not meet the norms as suggested by Dutch researchers for chicon production as was the case from the N x K trial (Chapter 4). Associated with K, Ca and Mg levels were also below those prescribed by these researchers, despite high soil levels. This indicates that environmental factors are influential in the way that root chicory responds to these nutrients. It is suggested that possibly the root norms for hotter climates should be lower than those reported for European chicon production conditions.

From the pot trial results it was apparent that clay type and percentage played a very important part in K behaviour and the plants ability to utilise K from the various pools. Indications are that root chicory has a preference for soils with a higher clay content (25-40%) with 2:1 clay soils performing well under micro-irrigation pending careful seed bed management.

The hypothesis that soil type played a significant role ($p<0.05$) in K behaviour and K fertiliser management was accepted.

CHAPTER EIGHT

FERTILISER RECOMMENDATIONS, CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK ON ROOT CHICORY (*Cichorium intybus* var. *sativum*)

8.1 Introduction

Four irrigated field trials were done, two (nitrogen x phosphorus x lime and nitrogen x potassium) ran for three seasons (2011/12, 2012/13, 2013/14) and two (acidity and boron x two different application methods) for two seasons (2013/14, 2014/15). A pot trial was also conducted (potassium x soil type) (2015/16). The field trials were conducted on a soil considered to be of moderate potential for root chicory at the Dundee Agricultural Research Station (DARS) and the pot trial was done at Cedara Agricultural Research Station (CARS) in KwaZulu-Natal (KZN). All field trials were leaf sampled at 60 days after sowing (DAS) and at harvest, while root sampling was done after the last harvest of each trial. The pot trial, planted on the 5 November 2015, was leaf sampled three times with the additional sampling done at 120 DAS while root sampling was also done at harvesting.

The relationship between the soil test value and plant response characteristics is an important one. Soil test values alone are insufficient to make decisions on fertiliser application rates to be applied to a particular crop. Calibration research therefore has to be embarked on and this is both expensive and time consuming and is unfortunately thus becoming increasingly rare worldwide.

In KwaZulu-Natal (KZN), the first calibration research exercise involved maize that was initially studied in the mid 1960's. This was followed by soyabeans, potatoes, cabbages and lucerne and a number of pasture species (Manson et al., 2012). These field experiments created a firm foundation to enable sound advice to be given to farmers on liming and fertiliser requirements from the Fertiliser Advisory Service at Cedara, outside Pietermaritzburg in KZN. This is part of the Department of Agriculture and Rural Development, and is an agricultural facility for the entire province. The Soil Science section processes about 35 000 soil samples per year (L. Thurtell, Scientific Manager, Department of Agriculture and Rural Development KZN pers. comm., 2016) as a soil fertility service to the agricultural sector. From the data produced for each topsoil sample (usually 0-15 cm) recommendations are given for fertiliser requirements based on the FERTREC software package that was first developed in 1977 (Manson et al., 2012).

However, with over a hundred crops to cater for by FERTREC an unrealistically large amount of calibration research would have to be done. To try and meet this requirement use is therefore made of international published literature coupled where possible with local field expertise to try and fill the void in detailed, field-based, local calibration research.

The research carried out during the present study represents the first attempt in South Africa to add information specifically for root chicory to the FERTREC database and thus contribute to its ongoing development. Although this field research was conducted at only one site (Dundee Agricultural Research Station (DARS)), on one particular soil type (an acidic sandy loam), both represent what are likely to be typical root chicory growing conditions in KZN. Due to the nature of this chapter, a certain amount of repetition from earlier chapters is necessary to present concise fertiliser findings that can be of use to the root chicory industry in KZN.

8.2 Primary nutrients (nitrogen, phosphorus and potassium)

8.2.1 Nitrogen

No soil test is performed for nitrogen (N) at Cedara for the reasons previously discussed (Section 3.3.1.2). Fertiliser recommendations are based on expected crop responses and on the assumption that there is little residual inorganic N from the previous crop in the soil, and that little organic N will be mineralised, either from soil organic matter or crop residues. Mid infra-red spectroscopy is used to estimate soil organic carbon and total N. The supply of N from these sources can be estimated by the farmer or adviser, and allowed for when recommending N application rates.

Cognisance should be taken that this study only concentrated on yield responses to various fertiliser levels and inulin (fructans) contents in the root were not determined. The possibility exists that with an increase in the application rate of N, inulin production could fall, similar to that found with the sugar content in sugar beet.

8.2.1.1 Optimal yield

Results from the three field trials that included N as one of the primary nutrients found that root chicory yield responded significantly $p < 0.001$ on an individual basis. The increase in yield can be described by a polynomial function (Figure 8.1) over all the N trials. Root

chicory grown in the low clay, low initial N soil under irrigation in warm conditions had a high N requirement. Root chicory responded positively even with 240 kg N ha⁻¹ but an important criterion to consider is root quality as determined by the number of diseased roots. The trials all showed a decline in root quality at around 160-180 kg N ha⁻¹ (Figure 8.2).

Leaf N at 180 kg N ha⁻¹ ranged from 3.5-3.7% at 60 days after sowing (DAS), while root N ranged from 0.5-1.1% at harvest. Leaf N levels are regarded by Campbell (2000) as reaching a critical level (10% growth reduction) for many plants at about 3% N. When the N in leaves drops below 2.75%, N deficiency symptoms appear and yield (<80% of maximum yield) and quality decline (Reuter and Robinson, 1997) for many plants. Good yields were still obtained in the present trials with leaf N of 3.4% but a distinct decline (10% growth reduction) was recorded at <3.0% N. Research on chicon production suggested roots at harvesting should have a target nutrient amount of between 0.7 to 1.3% N (RTFA 2010, 2015). However, >1.2% N increases the sensitivity of the chicory heads to bacteria and to pith deformations (brown pith), which result in a decrease in quality according to Marle and Roux (1991).

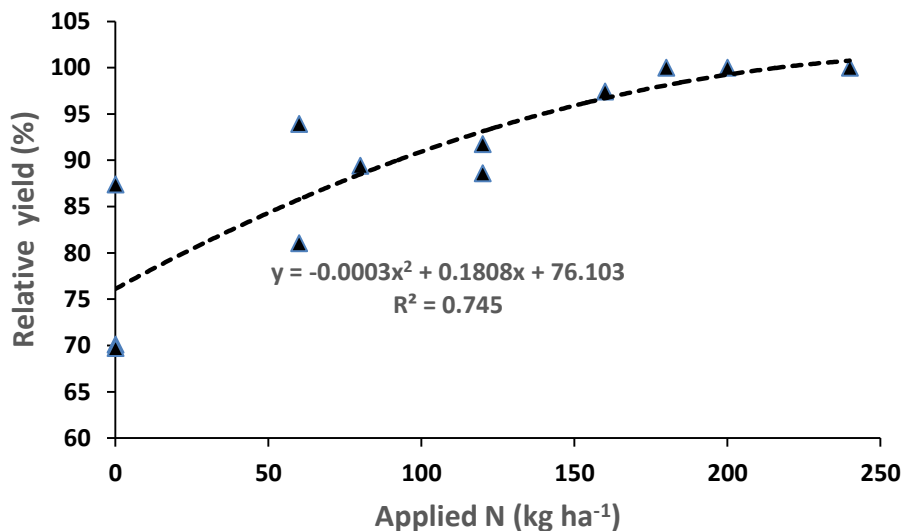


Figure 8.1: Relative yield as a function of applied nitrogen (N) over three N trials (n=23) (CV% 14.6, l.s.d. 5.4835, S.E.M. 5.6371 all at p<0.05).

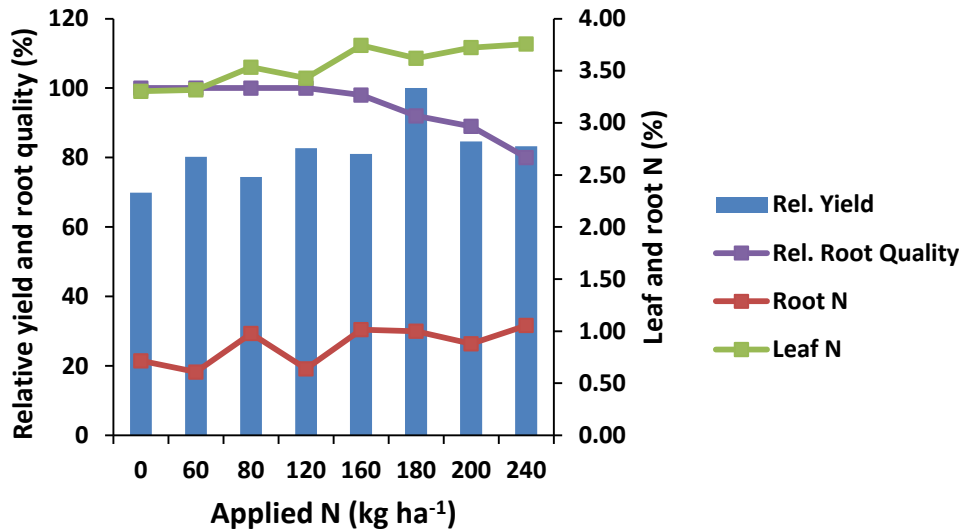


Figure 8.2: Relative yield and root quality, leaf nitrogen (N) at 60 days after sowing (DAS) and root N at harvest, with different N treatments over all N trials (Yield and leaf n=23, root n=9) (Yield: CV% 14.6, l.s.d. 5.4835, S.E.M. 5.6371; Leaf: CV% 9.8, l.s.d. 0.2411, S.E.M. 0.3344; Root: CV% 18.4, l.s.d. 0.0933, S.E.M. 0.1286 all at p<0.05).

8.2.1.2 Soil and plant analysis recommendations

Soil

Irrigation target yield 45-50 t ha⁻¹: 160-180 kg N ha⁻¹. Plant with 30% N the balance at 40 DAS. After application soils should be irrigated.

Irrigation target yield 30-35 t ha⁻¹: 60-80 kg N ha⁻¹. Plant with total N requirement. After application soils should be irrigated.

Plant

At 60 DAS the youngest unfolded leaf should be sampled. Forty leaves should be sampled. The result should be 3.5-3.7% N. At harvest root N should be in the range 0.9-1.1%. Both leaf and root measurements are on a dry matter basis.

8.2.2 Phosphorus

Chicory does not appear to require large amounts of P fertiliser. Phosphorus applied gave a positive trend with yield but the overall effect was non-significant.

8.2.2.1 Optimal yield

A relative yield of 96% at P40 was not significantly different to the higher treatment applications. Thus the soil P at P40 as determined from the trial (31 mg P L⁻¹) is the same as that predicted from Equation 8.1 (30.7 kg P ha⁻¹). Leaf P percentage across the treatment range was fairly constant at 0.40% P at 60 DAS. Hochmuth et al. (2009) reported that most recently matured leaves of vegetables contain 0.25 to 0.60% P on a dry weight basis. Root P was also relatively constant at about 0.20% P at both harvests. A target nutrient amount for roots of between 0.225 and 0.275% P has been advocated for chicon production by Dutch researchers (RTFA 2010, 2015).

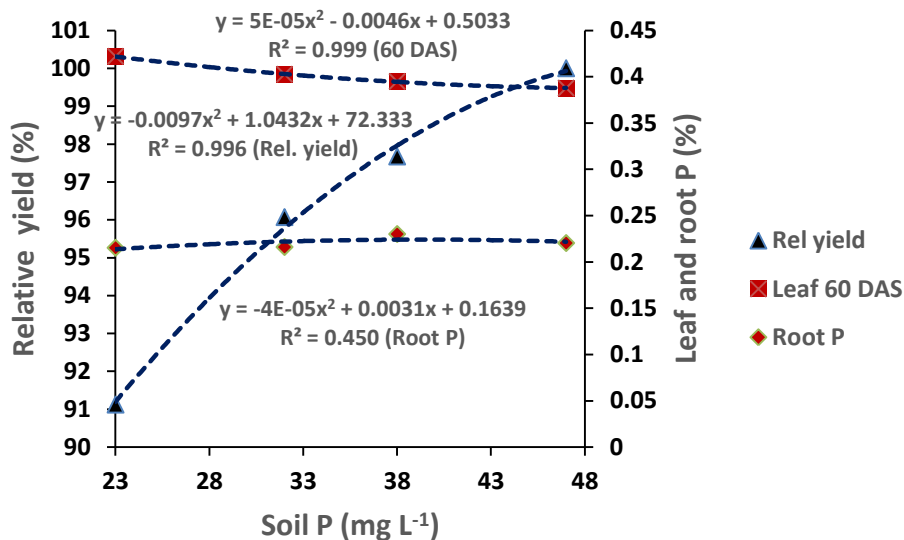


Figure 8.3: Relative yield, leaf phosphorus (P) at 60 days after sowing (DAS) and root P at harvest with different soil P values (Yield and leaf n=8, root n=2) (Yield: CV% 13.2, l.s.d. 3.217, S.E.M. 4.846; Leaf: CV% 13.3, l.s.d. 0.0247, S.E.M. 0.0533; Root: CV% 9.8, l.s.d. 0.0107, S.E.M. 0.0215 all at p<0.05).

8.2.2.2 Soil and plant analysis recommendations

Soil

Soil target phosphorus (P) values are dependent on soil texture, which is reflected by sample density. Target values are lower for clay soils (low sample density) and higher for sandy soils (high sample density) because the chemical extractant used (Ambic-2) is less effective at removing plant-available P from clays than from sands. It is necessary to adjust the target P

value according to the sample density of the soil, which is done by the Fertiliser Advisory Service using the FERTREC software (Manson et al., 2012).

The P requirement factor (PRF) related to the soil target value is the amount of P required to raise the soil test P value by 1 mg L⁻¹. Field experimental data, mainly from maize research, have been used to determine the relationship between sample density and PRF. This varies with the soil type, and is related to the sample density and can be described by Equation 8.1 (Johnston et al., 1991).

$$\text{PRF} = [31.37 \times (\text{sample density})^2] - [94.13 \times (\text{sample density}) - 73.54] \dots \text{Equation 8.1}$$

where PRF is the P requirement factor (kg P ha⁻¹).

The equation is valid for soils with sample densities from 1.00 to 1.45 g mL⁻¹. For soils with sample densities <1.00 g mL⁻¹ and >1.45 g mL⁻¹ PRF's of 10.78 and 3.00, respectively, are used.

A 30/16 target P should be aimed for i.e., 30 mg L⁻¹ for sample densities of 1.25 g mL⁻¹ and 16 mg L⁻¹ for sample densities of ≤1 g mL⁻¹. A minimum starter of 20 kg P ha⁻¹ is recommended, except when the soil is high in P (>120 mg L⁻¹) then no P fertiliser is recommended (Manson et al., 2012). Phosphorus should be incorporated at planting or as close to planting as possible. If the soil sample requires more than 60 kg P ha⁻¹ in Bioclimatic Regions 3, 4 or 6 (Natural Resources Working Group, 2013), the maximum of 60 kg ha⁻¹ (Manson et al., 2012) would apply due to P fixation (Johnston et al., 1991; Bainbridge et al., 1995) in the highly-weathered soils of these rainfall areas.

Target P values apply only to soils with specific sample densities, and it is necessary to adjust the target P according to the sample density of the soil sampled. Table 8.1 can be used to achieve this or the formula given in Equation 8.2.

$$\text{Target P} = \mathbf{a} \times \text{sample density (g mL}^{-1}\text{)} - \mathbf{b} \dots \text{Equation 8.2}$$

where a and b are constants i.e., a = 56 and b = 40 for a 30/16 P target (Manson et al., 2012). Sample density values used in this equation are restricted to the range 1.00 to 1.45 g mL⁻¹ (Manson et al., 2012).

The present research has shown that root chicory responded significantly to P treatments at $p < 0.05$. The greatest response occurred with the addition of 40 kg P ha^{-1} (Figure 8.3). The initial soil P was 23 mg P L^{-1} and this increased to 31 mg P L^{-1} with this applied amount (Figure 8.3).

For the DARS soil (sample density of 1.33 g mL^{-1}) the FERTREC model would use a PRF of $3.84 \text{ kg P ha}^{-1}$ to raise the soil P by 1 mg L^{-1} (Equation 8.1). This is lower than the PRF observed for the trial on the addition of 40 kg P ha^{-1} (calculated PRF of 5.0 kg P ha^{-1}).

The Ambic-2 soil P that is suggested for adequate yield is 31 mg L^{-1} for soils with a sample density of 1.33 g mL^{-1} . Applying increasing amounts of P at planting to a depth of 15 cm resulted in a highly significant ($p < 0.001$) increase in soil P

Table 8.1: Values of target phosphorus (P mg L⁻¹) for soils of different sample density relative to the values for target P for sample densities of 1.25 and 1.00 g mL⁻¹, and the variation in P requirement factor (PRF) with sample density (Manson et al., 2012)

Target P	Sample density (g mL ⁻¹)									
	≤1.00	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	≥1.45
30/16	16	19	22	25	27	30	33	35	38	41
PRF	10.78	9.29	7.95	6.78	5.76	4.89	4.19	3.64	3.24	3.00

Plant

Leaf P at 60 DAS did not change significantly with the addition of P but remained fairly constant in the range 0.39 to 0.41%; growers should aim for 0.40% P. Root P, like that in the leaf, did not have a wide range between the control and high P applications (0.22-0.23% P), with the highest yield occurring at 0.23% P. Root P should be within the range 0.20 to 0.25%; both plant and root recommendations are on a dry-matter basis.

8.2.3 Potassium

Potassium is generally used by plants in larger amounts than any other nutrient except N and root chicory is no exception.

8.2.3.1 Optimal yield

Root chicory did not respond significantly to applied K at $p < 0.05$. It was found, however, that the crop significantly depleted the subsoil K especially in the low K applications (0 and 50 kg ha⁻¹). Due to the crop being deep rooted cognisance has to be taken of the subsoil K prior to making a recommendation and the soil should be analysed for subsoil K. In KZN, 100 mg L⁻¹ in the subsoil is regarded as high (Manson et al., 2012); the trial site initially had 78 mg L⁻¹. Forage chicory in Sweden was found to utilise about 80 kg K ha⁻¹ from the subsoil without the addition of applied K (Witter and Johansson, 2001). With sub-optimal fertilisation of K in the topsoil, pressure is put on subsoil K reserves, ultimately depleting subsoil K. Soil tests for K in only the 0-15 cm layer can underestimate soil K availability for root chicory. In fertile soils, the fertiliser K has a low contribution to root chicory nutrition. In the field trial the soil K dominated the K nutrition of root chicory and this may explain the relatively small effects of fertiliser K on yield. Less than half of the fertiliser K, on average, was absorbed by the root chicory.

From the present trial K balance sheet the apparent utilisation coefficient was highest with the application of 150 kg K ha⁻¹ and a soil K of 133 mg K L⁻¹ (Figure 8.4). Leaf K of 4.5 to 4.6% (60 DAS) was found in the higher yielding plots (Figure 8.4). Ćustić et al. (2003) working with red head chicory (*Cichorium intybus* var. *foliosum* L.) found that K in head chicory ranged from 3.27 to 5.16% K in the plant tissue at 60 DAS whereas the current trial results ranged from 3.15 to 6.1% K. Deficient vegetable plant leaves usually contain less than 1.5% K (Hochmuth et al., 2009). Higher yields had a root K of 1.2 to 1.3% (Figure 8.4), below the target values of between 1.5 and 2% K found by chicon researchers for forcing (Sarrazyn and Deckers, 1991).

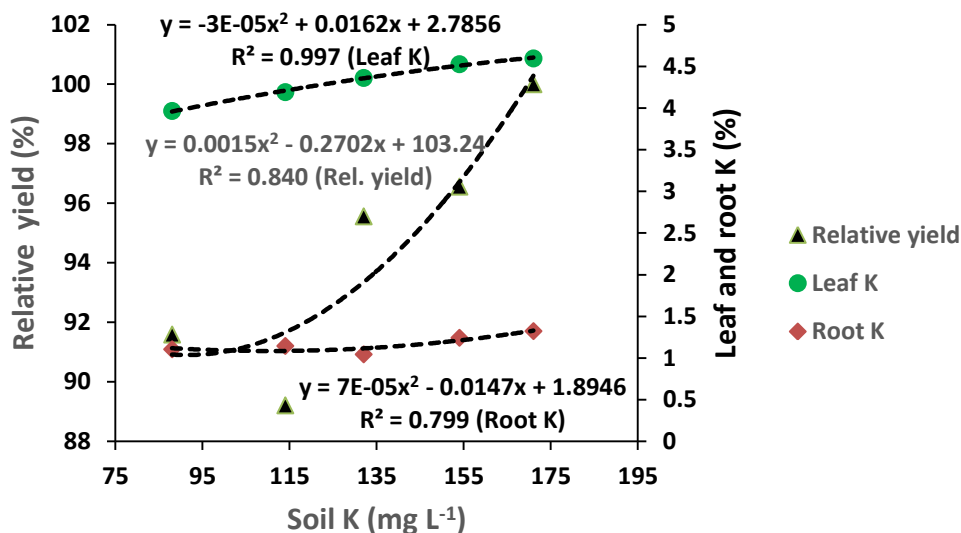


Figure 8.4: Relative yield, leaf potassium (K) at 60 days after sowing (DAS) and root at harvest with different soil K values (Yield and leaf n=9, root n=3) (Yield: CV% 18.2, l.s.d. 7.734 , S.E.M. 7.455; Leaf: CV% 10.7, l.s.d. 0.4029, S.E.M. 0.4010; Root: CV% 16.8, l.s.d. 0.1629, S.E.M. 0.1971 all at p<0.05).

8.2.3.2 Soil and plant recommendations

Soil

The K fertiliser recommendation is calculated to raise the soil K test to the "target K" level of the crop to be fertilised. Where the applied K is incorporated into the soil, it is assumed that 2.5 kg K ha⁻¹ is required to raise the soil K test by 1 mg L⁻¹ using Equation 8.3 (Johnston et al., 1999).

$$\text{Recommended K (kg ha}^{-1}\text{)} = (\text{"Target K"} - \text{soil K}) \times 2.5 \dots \dots \dots \text{Equation 8.3}$$

A target soil K of 150 mg L⁻¹ is suggested, although 133 mg L⁻¹ was the turning point when only K was applied, the N x K turning point was not reached. Soil sampling should be done to a greater depth (at least 60 cm) to determine subsoil K contribution. Subsoils high in K can reduce the applied K required as the root is able to extract K from a greater depth. The effect of clay type especially 2:1 types needs to be determined using the "nitric K" method and a reserve value determined for these soils.

When no K fertilisation was used, a relatively low 60 kg N ha⁻¹ was sufficient in this trial. However, when the K fertilisation was high (150-200 kg K ha⁻¹), the N fertilisation needed to

be increased to 120-180 kg N ha⁻¹ on soils such as that at the DARS, that have a low clay content, to ensure an adequate total N content in the leaf.

Plant

The highest yield was attained with a root value of 1.24% K. Based on this trial (and the literature review) a leaf target (at 60 DAS) of 4.5-5% and a root target (at harvest) of 1.2 to 1.5% K are suggested.

8.3 Secondary nutrients (calcium and magnesium)

8.3.1 Calcium

There was a highly significant yield response to dolomitic lime at $p < 0.001$ in the lime trials (Figure 8.5). The initial soil Ca for the N x P x L trial was 405 mg L⁻¹ with a steep increase in relative yield between L0 and L2 indicating a response to lime as the acid saturation percentage was low. Likewise, the N x L trial with even lower initial soil Ca (369 mg L⁻¹) showed a highly significant response from L0 to L3. The L2 and L3 soil Ca levels were 438 and 445 mg L⁻¹, respectively. Above 440 mg Ca L⁻¹, there was no response to lime and therefore 440 mg Ca L⁻¹ is a safe target. The trial soils had an average Ca saturation percentage of 61.14% over the trial duration. At the highest level of lime (L8) there was no evidence of a decrease in uptake of Mg and K probably due to the relatively low levels of Ca prevalent even at this liming rate on these soils.

Leaf Ca, at the higher relative yields, ranged between 0.92 and 1.03% at harvest (Figure 8.5) and is within the range of between 0.6 and 5.0% Ca given by Hochmuth et al. (1993, 2009) for healthy, most recently matured vegetable leaves. Root Ca ranged between 0.16 and 0.21% at harvest. Chicon producers favour a slightly higher value of 0.27-0.29% (RTFA 2010, 2015). Root and leaf percentages were both significantly higher ($p < 0.001$) with applied lime. A soil Ca recommendation of 440 mg L⁻¹ with a leaf Ca between 0.92 and 1.03% and root calcium from 0.16 to 0.21% at harvest are recommended (both on a dry matter basis). These can be regarded as adequate levels, although maximum yields on other soils may be possible at concentrations outside these ranges.

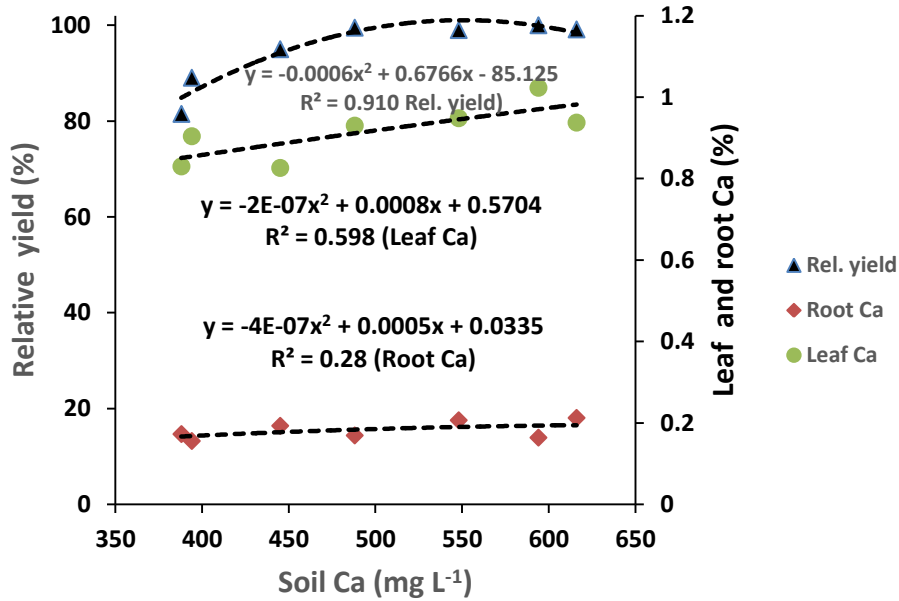


Figure 8.5: Relative yield, leaf calcium (Ca) at 60 days after sowing (DAS) and root Ca at harvest with different soil Ca (Yield and leaf n=14, root n=6) (Yield: CV% 11.2, l.s.d. 5.0216, S.E.M. 4.4772; Leaf: CV% 15.5, l.s.d. 0.0530, S.E.M. 0.0733; Root: CV% 12.3, l.s.d. 0.0148, S.E.M. 0.0219 all at p<0.05).

8.3.2 Magnesium

Soil Mg was significantly correlated with all levels of lime application but the greatest increase in Mg was with a change from L2 (93 mg Mg L⁻¹) to L4 (107 mg Mg L⁻¹) (Figure 8.6). The change in soil Mg was not of the same magnitude as Ca. This is as result of Mg being less strongly adsorbed to cation exchange sites resulting in less exchangeable Mg in soils (Foth, 2003) and a lower Mg content in the lime. The average Mg saturation percentage was 20.16% over the trial duration. Magnesium has the potential to significantly decrease the uptake of K and Ca although this was not evident at the high application rates of lime as the Mg levels were probably still too low to have this effect. Likewise, there was also no apparent effect on P uptake by increasing Mg content. In all likelihood, the positive yield response was attributable to lower aluminium or higher Ca levels, but the results suggest that 100 mg L⁻¹ soil Mg on a sandy soil is adequate for root chicory. This soil Mg level is favoured as Huber and Jones (2013) report that Mg increases the resistance of tissues to degradation by some pectolytic enzymes of macerating or soft rotting pathogens; this is an important consideration as root chicory is susceptible to soft root rots. However, MAFF (1988) suggested 60 mg L⁻¹ and Alt et al. (1999) suggested 67 mg L⁻¹ for a variety of vegetable crops on all soils.

Leaf Mg had a moderately significant association with P ($p=0.010$) and N ($p=0.019$) but was just non-significant with lime. The interaction of N and time on leaf Mg was significant ($p=0.014$). Leaf Mg values at the higher relative yield percentages varied between 0.30 and 0.38% (60 DAS) (Figures 8.6). Hochmuth et al. (1993, 2009) reported Mg values between 0.2 and 0.8% in recently matured, healthy vegetable leaves.

Root Mg stayed relatively constant between 0.11 and 0.13% at harvest while chicon producers aim for between 0.13 and 0.15% Mg (RTFA 2010, 2015). Based on the trial results, a soil Mg recommendation of 100 mg L^{-1} with a leaf Mg of 0.3 to 0.4% and a root Mg from 0.11 to 0.13% are recommended as being within the adequate range, the latter two on a dry matter basis.

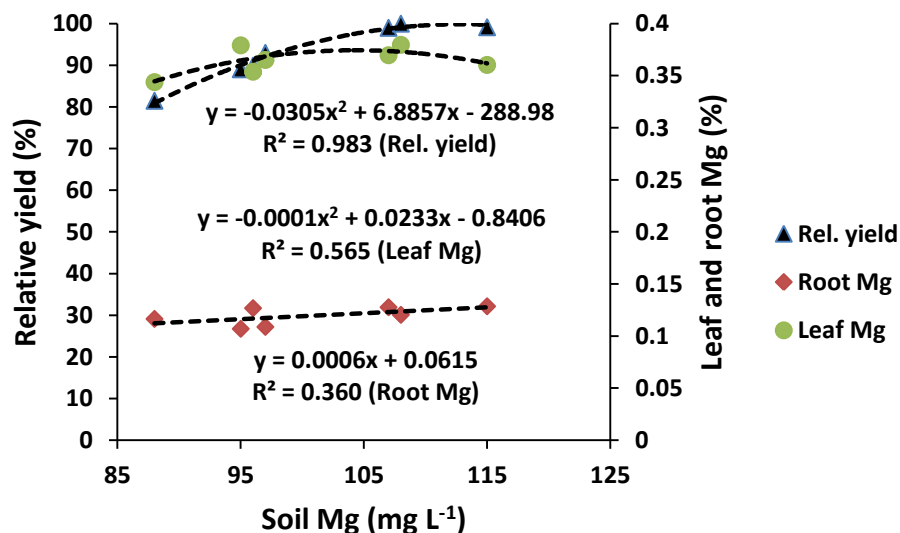


Figure 8.6: Relative yield, leaf magnesium (Mg) at 60 days after sowing (DAS) and root Mg at harvest with different soil Mg (Yield and leaf $n=14$, root $n=6$) (Yield: CV% 11.2, l.s.d. 5.0216, S.E.M. 4.4772; Leaf: CV% 10.3, l.s.d. 0.0285, S.E.M. 0.0360; Root: CV% 12.1, l.s.d. 0.0088, S.E.M. 0.0126 all at $p<0.05$).

8.4 Acid saturation

Lime was responsible for increased yields in both trials in the integrated as well as the individual harvests. The highest lime treatment (8 t ha^{-1}) produced the highest yield. This was expected as the initial soil pH(KCl) was below 4.0. The greatest increase in yield occurred

from the control to the first lime treatment level in both trials. Not only was the change in pH a factor but the soils were inherently low in Ca and Mg and this could have contributed to the yield response. The effect of lime was more noticeable in the second harvest. Root chicory seemed to show a high degree of resilience to the highest rate of lime application (soil pH 5.4 at 8 t lime ha⁻¹). The continuing response to lime in the field experiment at the highest rate applied suggests that chicory is tolerant of soils with higher pH, as has been reported by other researchers who worked on neutral to alkaline soils

The results showed a significant change in soil chemistry over time on this soil, which has restricted permeability in the subsoil. The possibility exists that root chicory is able to increase topsoil pH thereby reducing aluminium solubility and toxicity by extracting deeper reserves of Ca, Mg, K and sodium from the subsoil, in addition to possible direct rhizosphere effects. It is surmised that a combination of factors resulted in this distinct change in topsoil chemical characteristics.

The field trial to investigate the acid saturation percentage requirements for root chicory experienced some challenges (Section 6.3.2.5). Acid saturation percentage had a positive and significant association with root yield within the range 6.89 to 24.56%. The positive association with pH, base saturation, and Ca and Mg saturation, as well as the positive association with acid saturation, indicates tolerance of root chicory to this acidity range. The second year of the N x P x L trial provided some further insight into the response of the crop to higher acid saturation percentages (Figure 8.7). The data were subjected to segmented regression analysis using the broken-stick method (Appendix 8.1). The breakpoint occurred at 21% acid saturation with a relative yield of 58.91%. Upjohn and Michalk (1999) in pot trials reported that forage chicory is tolerant to an acid saturation percentage of 41%. As a preliminary recommendation $\leq 20\%$ acid saturation is regarded as an initial target until further research can be done. This is recommended as the crop is often rotated with maize, which has a permissible acid saturation percentage of 20% (Manson et al., 2012).

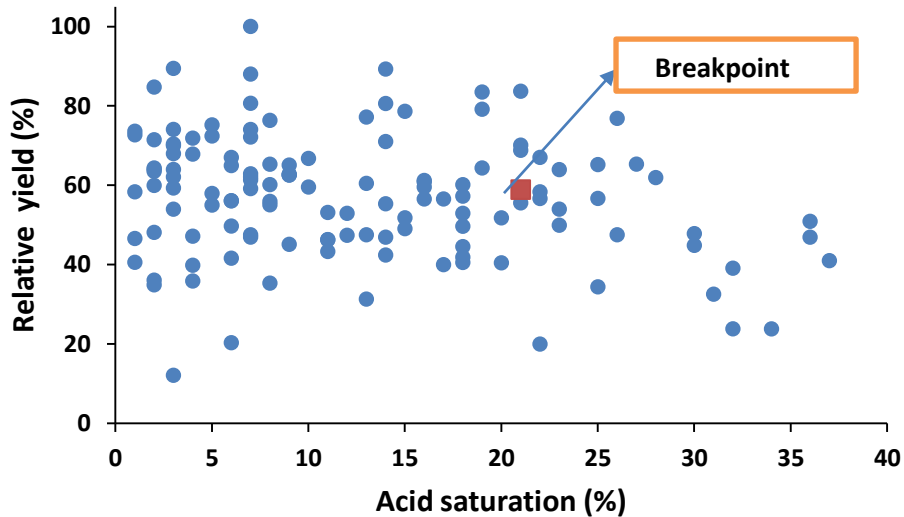


Figure 8.7: Relative yield and acid saturation for the second harvest of the nitrogen x phosphorus x lime trial with the break-point indicated (n=2) (Yield: CV% 12.8, l.s.d. 2.338, S.E.M. 4.703 all at $p < 0.05$).

8.5 Boron

Boron showed no significant relationships with yield (Figure 8.8). The most significant root quality finding, however, was the incidence of multiple rooting and heart rot in the control plots. There was a highly significant relationship between applied B and topsoil B ($p < 0.001$). The method of application (soil versus foliar) over time was also highly significant ($p < 0.001$) with the amount of B in the topsoil. In the subsoil, B was significant at the 5% level of significance but the method of application was non-significant. Applied B leached relatively rapidly through the profile and was found in the deeper clay-enriched subsoil at 60 cm. Leaf B and the method of application showed a highly significant interaction ($p < 0.001$) for the second leaf sampling. Boron in the root was significant at the 5% level with added B as well as with the method of application.

Soil B extracted using the hot water extraction procedure gave soil B levels that are regarded in the literature as very low (Section 5.3.5). From the trial results (and literature review) a soil B of $> 0.27 \text{ mg kg}^{-1}$ with a leaf boron $\geq 25 \text{ mg kg}^{-1}$ and a root value of $8\text{-}11 \text{ mg B kg}^{-1}$ seem to be adequate (Figure 8.8).

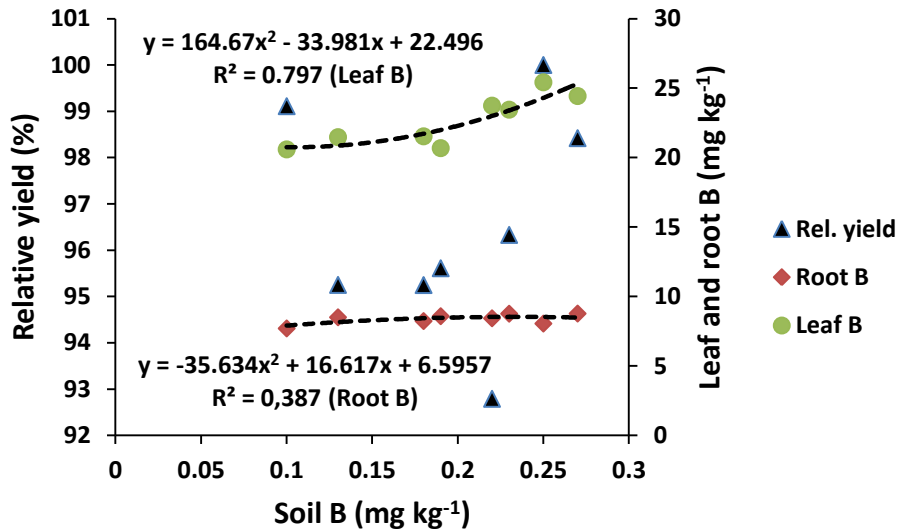


Figure 8.8: Relative yield, leaf at 60 days after sowing (DAS) and root boron (B) at harvest with different soil B (Yield and leaf n=8, root n=6) (Yield: CV% 15.6, l.s.d. 5.588, S.E.M. 5.549; Leaf: CV% 8.5, l.s.d. 4.2728, S.E.M. 1.931; Root: CV% 8.1, l.s.d. 0.9746, S.E.M. 0.6839 all at $p < 0.05$).

8.6 Economic yield

The most significant nutrient effects in the trials were those from N and this plays a central role in root chicory production. An analysis (Appendix 8.2) of the gross margin for three N application rates using contractors illustrates that root chicory has a yield break-even point near 20 t ha⁻¹ given the current (2017) price of R1 200.00 t ha⁻¹ (wet root) (MBB Consultants, 2016). A slight variation in gross margin can be achieved using different combinations of fertilisers but the trend is similar to that portrayed in Appendix 8.2. Of the N treatments tested, the highest gross margin was realised with 180 kg N ha⁻¹ (Figure 8.9); higher N application rates resulted in an increase in root diseases. The next-best gross margins according to the trial results were with 120 and 60 kg N ha⁻¹, respectively, but these gave lower yields (Figure 8.9). Parameters for root chicory from the trials give an indication of the levels of nutrients required to produce a crop that gives the best gross margin (Table 8.2). However, cognisance needs to be taken that even with a gross margin of R9 342 ha⁻¹ at 30 t ha⁻¹ (MBB Consultants, 2016) using the current price of R1 200 t⁻¹ (Appendix 8.3), the returns from chicory do not compare favourably with competing crops such as cabbage, green maize, butternut, spinach and sweet potato (Appendix 8.4). At R1 400 t⁻¹ there is an increase in the gross margin of chicory to R15 342 ha⁻¹ and this surpasses the least profitable vegetable, sweet potato (Appendix 8.5). The trials were conducted on moderate-potential soils and so higher yields could undoubtedly be achieved on higher-potential soils. The

results reflect average yields for farmers and therefore the gross margins are indicative of the returns that could be expected. Long-term results from commercial production in Belgium and the Netherlands report average yields of 46.8 and 42.7 t ha⁻¹, respectively (Marinussen et al., 2012). The main producers of chicory in Europe base their N application on a residual nitrogen of 60 kg N ha⁻¹ with 70 kg N ha⁻¹ applied for a total of 130 kg N ha⁻¹. Temperature differences between KZN and northern Europe, soil type and whether dryland or irrigated play a significant role in N availability and usage by the plant.

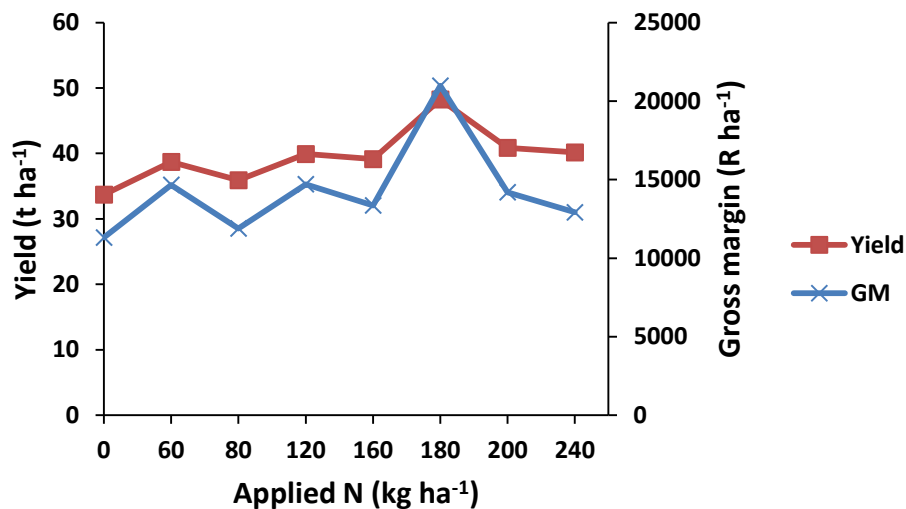


Figure 8.9: Gross margin (GM) and yield at different nitrogen (N) application rates with a chicory price (wet yield) of R 1 200 ton⁻¹.

Table 8.2: Suggested soil, leaf and root targets for the best gross margin (2017) for root chicory under irrigation on a moderate-potential sandy loam soil in KwaZulu-Natal

	Application rate (kg ha ⁻¹)	Soil target	Leaf range at 60 DAS [#]	Root range at harvest
Nitrogen	160 - 180	na ^{\$}	3.4 - 3.7%	0.9 - 1.1%
Phosphorus		≥31 mg L ⁻¹	0.4 - 0.45%	0.2 - 0.25%
Potassium		≥145 - 150 mg L ^{-1*}	4.5 - 5%	1.2 - 1.5%
Calcium		≥440 mg L ⁻¹	0.92 - 1.03%	0.16 - 0.21%
Magnesium		≥100 mg L ⁻¹	0.30 - 0.40%	0.11 - 0.13%
Boron	2	hws [£] >0.27 mg kg ⁻¹	≥25 mg kg ⁻¹	8 - 11 mg kg ⁻¹
Acid saturation		≤20%		

[#] DAS – days after sowing

^{\$} na – not applicable

[£] hws – hot water soluble

* With leaf material returned to the soil at harvest.

8.7 Conclusions for improvement to the fertility requirements of root chicory

8.7.1 Nitrogen

The current recommendation is 75-150 kg N ha⁻¹ (Table 8.3). Root chicory reacts favourably to N. In KZN, where chicory is irrigated, soil texture and economic considerations play an important role in the determination of the amount of N to apply. A sandy loam soil has the ability to produce a high yielding crop with 160-180 kg N ha⁻¹. However, caution is needed if this amount is exceeded as root quality deteriorates. A relative yield of 90% can also be achieved with a lower N application of 60-80 kg N ha⁻¹ and so the application rate would then depend on the profit margin. Soils with a higher clay percentage would in all likelihood require less applied N to that found in the current trials due to slightly higher initial soil N (depending also on the preceding crop) and reduced leaching.

Leaf N at 60 DAS can be used to determine the crop's N status, with 3.5 to 3.7% N reflecting adequate N for a high yield (>45 t ha⁻¹). A split application of N at 60 DAS can be used on low clay soils (<15%) to extend the availability of N to the crop. Root N of 0.9-1.2% for a similar yield was found; root N levels >1.2% should be avoided due to the increased probability of root diseases.

Table 8.3: Current versus recommended fertiliser requirements for the best gross margin (2017) conditions under irrigation on a moderate potential sandy loam soil in KwaZulu-Natal

	Current soil rec.	Rec ¹ . soil	Rec. leaf* (60 DAS ²)	Rec. root* (220 DAS)
Nitrogen	75-150 kg ha ⁻¹	60-180 kg ha ⁻¹	3.4 -3.7 %	0.9-1.2 %
Phosphorus ³	30:16 mg L ⁻¹	30:16 mg L ⁻¹	0.4-0.45 %	0.2-0.25 %
Potassium ⁴	200 mg L ⁻¹	145-150 mg L ⁻¹	4.5-4.7 %	1.2-1.3 %
Calcium	No rec.	≥440 mg L ⁻¹	0.92-1.03 %	0.16-0.21 %
Magnesium	≥100 mg L ⁻¹	≥100 mg L ⁻¹	0.30-0.39 %	0.11-0.13 %
Acid saturation (%)	≤1	≤20	not applicable	not applicable
Boron ⁵	No rec.	2 kg ha ⁻¹	≥25 mg kg ⁻¹	8-11 mg kg ⁻¹

* No current recommendation for either leaf or root

¹Rec: Recommendation; ²DAS – days after sowing; ³At 1.25 and ≤1 g mL⁻¹ sample density respectively; ⁴With leaf material returned to the soil at harvest. ⁵ On low clay (<15%) soils

8.7.2 Phosphorus

The current recommendation is dependent on sample density with a target of 30/16 (Table 8.3). The former value refers to a soil with a sample density of 1.25 g mL⁻¹ while the latter refers to soils ≤1.00 g mL⁻¹. The P requirement of root chicory is not high, but it is nevertheless an important element. On the sandy loam soil (sample density 1.33 g mL⁻¹) a soil P of 31 to 35 mg L⁻¹ was sufficient. On soils of a lower sample density, less will be required. The current recommendation by CARS when extrapolated for different soil textures is acceptable. There are currently no recommended levels for either leaf or root P. A leaf value of ≥0.40% P taken at 60 DAS proved adequate for higher yielding plots (>45 t ha⁻¹) and for roots it was established that 0.2-0.25% P at harvest was adequate for a similar yield.

8.7.3 Potassium

The current recommendation is 200 mg K L⁻¹, based on topsoil (0-15 cm) sampling (Table 8.3). However, soil sampling of both the topsoil and subsoil should be done to determine adequacy levels as subsoil K can be utilised by this deep-rooting crop. A target topsoil K of

133 mg L⁻¹ is recommended from the trial results. However due to the N x K yield curve not reaching its maximum, 145 to 150 mg K L⁻¹ is suggested until further research can be done. Like N, a split application of K can be practiced at 60 DAS on low clay soils (<15%). Leaf K of 4.5 to 4.7% provided the highest yield (>45 t ha⁻¹) when sampled at 60 DAS. Root levels at harvest with a K percentage of 1.2-1.3% proved sufficient for that yield. Cognisance needs to be taken of clay percentage and type as K is dynamic in the sense that it is easily leached or fixed pending on the nature of these two determinants as these played a prominent part in the yields obtained.

8.7.4 Lime and acidity

Chicory responded to dolomitic lime. It was found to tolerate high levels of lime (8 t ha⁻¹) without undue stress. A soil Ca level of 440 mg L⁻¹ with a soil Mg of >100 mg L⁻¹ gave high yields (>45 t ha⁻¹). Leaf Ca (0.92-1.03%) and Mg (0.30-0.39%) were adequate for ≥45 t ha⁻¹ yield. Root levels at harvest for Ca (0.16-0.21%) and Mg (0.11-0.13%) were found to be adequate. The upper acid saturation percentage threshold was not determined but preliminary results from the current trials indicate that chicory appears able to withstand relatively high levels of up to 25%; this differs substantially from the current recommendation of 1% currently used by CARS. Since chicory will mainly be used in a crop rotation with maize a permissible acid saturation of 20% is advocated.

8.7.5 Boron

Chicory yield did not respond significantly to B either soil or foliar-applied but there was a significant interaction between B treatment and multiple rooting and heart rot. The crop proved tolerant to relatively high levels of up to 3.5 kg B ha⁻¹. The leaf range for a good harvest was found to be ≥25 mg kg⁻¹ and 8-11 mg kg⁻¹ in the root at harvest was recorded for the low clay soil (8.3%). Due to multiple rooting and heart rot incidences 2 kg ha⁻¹ of B is recommended as a soil or equivalent foliar application on low clay soils (<15%).

8.8 Future research

From the results of the present study a number of areas for further soil fertility research have been identified in addition to other soil fertility areas not directly covered by this research.

8.8.1 Nitrogen

Inulin production is becoming important internationally. There is a need for the quantification of the N effect on inulin production to determine the optimum application rates for root and inulin production and to compare it to those found in this research. The determination of the threshold of N application rates on root quality is important for processing. The timing of N application on soils with various textures to determine the best practice under irrigation management needs further work.

8.8.2 Phosphorus

The importance of soil texture on the required P levels for satisfactory yields and how efficient root chicory is at extracting P from soils of differing texture, mineralogy and acid saturation percentage and the manner in which different treatment levels of P might influence the inulin content of the plant all require investigation.

8.8.3 Potassium

The amount of K extracted from the subsoil and its contribution to the K needs of the plant requires further investigation. The point of luxury K consumption for different soil types should be ascertained to understand the fertility requirements more fully. Quantification of the relationship between N application and K leaching and the subsequent usage of leached K will provide further insight into the fertility equilibrium between these two macronutrients. Since inulin content is seen as being important in South Africa, as it is internationally, the effect of different levels of K (in conjunction with N) on the inulin content of the plant requires quantification.

The method of non-exchangeable K extraction for routine laboratory analysis requires improvement as the methodology used in this study (nitric acid) is fairly time consuming. Use of mid-infrared techniques might prove worthy of consideration once correlation study results are known. This information could prove invaluable as an extra aid for site-specific K fertilisation recommendations linked to clay type.

8.8.4 Boron

The upper and lower levels of B tolerance for chicory under irrigated field conditions need further evaluation. Different extraction procedures to determine soil B levels that are best suited to root chicory need evaluation and testing by correlation to leaf B results.

The quantification of crop responses in different crop rotations, following root chicory, using different B treatments needs further investigation. In addition, soil types, textures and acid saturation percentages, under field conditions, could be used as variables to determine residual B build-up.

8.8.5 Acid saturation/alkalinity tolerance

Acid tolerance levels under irrigation management with various N fertilisers on different soil types need to be quantified. The upper limits of base saturation / pH that root chicory can tolerate needs determining and it is very important to establish if root chicory has the ability to increase the growth medium pH and thus reduce Al solubility and toxicity.

8.8.6 Organic matter response

Root chicory could show a change in yield and inulin response to different levels of organic matter in the soil (using organic carbon or organic N concentration as an index) in relation to set fertility practices. These should be evaluated against the current soil fertility norms and modifications proposed.

REFERENCES

- Adams, F. (1980). Interactions of phosphorus with other elements in soils and in plants. *The role of phosphorus in agriculture*, 655-680.
- Adams, P and Ho, L.C. (1993). Effects of environment on the uptake and distribution of calcium in tomato and on the incidence of blossom-end rot. *Plant and Soil*, 154(1), 127-132.
- Agriculture in South Africa. (1994). Agricultural production. Chris van Rensburg Publications. Johannesburg. 96pp.
- Agricultural Research Council (2016). ARC-ISCW Agro-Climatology database ARC-Institute for Soil, Climate and Water, Pretoria, South Africa.
- Aitken, R. L., Jeffrey, A. J., and Compton, B. L. (1987). Evaluation of selected extractants for boron in some Queensland soils. *Soil Research*, 25(3), 263-273.
- Alfaro, M. A., Jarvis, S. C., and Gregory, P. J. (2003). Potassium budgets in grassland systems as affected by nitrogen and drainage. *Soil Use and Management*, 19(2), 89-95.
- Ali, Z., Ganie, S. H., Narula, A., Abdin, M. Z., and Srivastava, P. S. (2013). Organic and inorganic fertilizers influence biomass production and esculin content in *Cichorium intybus* L. *Journal of Phytology* 4(5), 55-60.
- Alleoni, L. R. F., and Camargo, O. A. D. (2000). Boron adsorption in soils from the State of São Paulo, Brazil. *Pesquisa Agropecuária Brasileira*, 35(2), 413-421.
- Allison, F. E., and Sterling, L. D. (1949). Nitrate formation from soil organic matter in relation to total nitrogen and cropping practices. *Soil Science*, 67(3), 239-252.
- Allison, L., Bollen, W. B., and Moodie, C. D. (1965). Total carbon. *Methods of soil analysis. Part 2. Chemical and microbiological properties*, 1346-1366.
- Alt, D., Ladebusch, H., and Melzer, O. (1999). Long-term trial with increasing amounts of phosphorus, potassium and magnesium applied to vegetable crops. In: *International Workshop on Ecological Aspects of Vegetable Fertilization in Integrated Crop Production*. 506, 29-36.
- Alt, D., and Rimmek, J. (1995). OSGAR – ein einfaches EDV-Programm für die Düngung. *Gemüse* 31, 162-166.
- Améziane, R., Deléens, E., Noctor, G., Morot-Gaudry, J. F., and Limami, M. A. (1997). Stage of development is an important determinant in the effect of nitrate on photoassimilate (¹³C) partitioning in chicory (*Cichorium intybus*). *Journal of Experimental Botany* 48(1), 25-33.
- Améziane, R., Limami, M. A., Noctor, G., and Morot-Gaudry, J. F. (1995). Effect of nitrate concentration during growth on carbon partitioning and sink strength in chicory. *Journal of Experimental Botany* 46, 1423-1428.

- Anthoni J., Humeau, C., Maia, E., Chebil, R.L., Engasser, J.M., and Ghoul, M. (2010). Enzymatic synthesis of oligoesculin: structure and biological activities characterisations. *European Food Research and Technology* 231(4), 571-579.
- Asad, A., Blamey F.P.C., and Edwards D.G. (2003). Effects of boron foliar applications on vegetative reproductive growth of sunflower. *Annals of Botany*, 92(4), 56-570.
- Askegaard, M., Eriksen, J., and Olesen, J. E. (2003). Exchangeable potassium balances in organic crop rotations on a coarse sand. *Soil Use and Management*, 19(2), 96-103.
- Assimakopoulos, I., Kosmas, C., Nychas, A., and Bovis, C. (1986). The effect of previous P additions on sorption indices of calcareous soils determined with commonly employed methods. *Journal of Plant Nutrition and Soil Science*, 149(5), 548-560.
- Baert, J.R.A., and Van Bockstaele, E.J. (1993). Cultivation and breeding of root chicory for inulin production. *Industrial Crops and Products* 1(2-4), 229-234.
- Bainbridge, S. H., Miles, N., Praan, R., and Johnston, M. A. (1995). Phosphorus sorption in Natal soils. *South African Journal of Plant Soil*, 12(2), 59-64.
- Bais, H. P., and Ravishankar, G. A. (2001). *Cichorium intybus* L– cultivation, processing, utility, value addition biotechnology, with an emphasis on current status and future prospects. *Journal of the Science of Food Agriculture*, 81(5), 467-484.
- Baldini, M., Danuso, F., Monti, A., Amaducci, M. T., Stevanato, P., and De Mastro, G. (2006). Chicory and Jerusalem artichoke productivity in different areas of Italy, in relation to water availability and time of harvest. *Italian Journal of Agronomy* 1(2), 291-308.
- Baligar, V. C., Duncan, R. R., and Fageria, N. K. (1990). Soil-plant interaction on nutrient use-efficiency in plants: an overview.
- Baligar, V. C., Fageria, N. K., and He, Z. L. (2001). Nutrient use efficiency in plants. *Communications in Soil Science and Plant Analysis*, 32(7-8), 921-950.
- Barloy, J., and Fernez, J. (1989). Synthesis on Jerusalem artichoke projects. In: *Second Workshop EEC on Jerusalem artichoke. Rennes* (pp. 6-8).
- Barrow, N. J. (1987). Modelling the reaction of anions and cations with soil. In: *Reactions with Variable-Charge Soils* (pp. 54-80). Springer Netherlands.
- Bartz, J. A., Geraldson, G. M., and Crill, J. P. (1979). Nitrogen nutrition of tomato plants susceptibility of the fruit to bacterial soft rot. *Phytopathology*, 69(2), 163.
- Bar-Yosef, B., Magen, H., Johnston, A. E., and Kirkby, E. A. (2015). Potassium fertilisation: paradox or K management dilemma? *Renewable Agriculture and Food Systems*, 30(02), 115-119.
- Bauer, P. J., and Carter, P. R. (1986). Effect of seeding date, plant density, moisture availability, soil nitrogen fertility on maize kernel breakage susceptibility. *Crop Science*, 26(6), 1220-1226.

- Beckett, P. (1964). Potassium-calcium exchange equilibria in soils: specific adsorption sites for potassium. *Soil Science*, 97(6), 376-383.
- Beckett, P. H. T., and Nafady, M. H. M. (1967). Studies on soil potassium. 6. Effect of K-fixation and release on form of K-(Ca+ Mg) exchange isotherm. *Journal of Soil Science*, 18(2), 244-262.
- Belesky, D. P., Turner, K. E., and Ruckle, J. M. (2000). Influence of nitrogen on productivity nutritive value of forage chicory. *Agronomy Journal*, 92(3), 472-478.
- Bell, R. W. (1997). Diagnosis prediction of boron deficiency for plant production. *Plant and Soil*, 193(1-2), 149-168.
- Bell, R. W., McLay, L., Plaskett, D., Dell, B., and Loneragan, J. F. (1989). Germination vigour of black gram (*Vigna mungo* (L.) Hepper) seed from plants grown with and without boron. *Crop and Pasture Science*, 40(2), 273-279.
- Bellaloui, N., and Brown, P. H. (1998). Cultivar differences in boron uptake and distribution in celery (*Apium graveolens*), tomato (*Lycopersicon esculentum*) and wheat (*Triticum aestivum*). *Plant and Soil*, 198(2), 153-158.
- Berger, K. C. (1949). Boron in soils and crops. *Advances in Agronomy*, 1, 321-351.
- Berger, K. C., and Truog, E. (1939). Boron determination in soils and plants. *Industrial and Engineering Chemistry Analytical Edition*, 11(10), 540-545.
- Berger, K. C., and Truog, E. (1940). Boron deficiencies as revealed by plant and soil tests. *Journal of the American Society of Agronomy*, 32, 297-301.
- Bertsch, P. M., and Thomas, G. W. (1985). Potassium status of temperate region soils. *Potassium in Agriculture*, 131-162.
- Bhal, G. S., and Toor, G. S. (2002). Influence of poultry manure on phosphate availability and the standard phosphate requirement of crop estimated from quantity-intensity relationships in different soils. *Bio-resource Technology*, 85(3), 317-322.
- Bingham, F. T. (1973). Salt tolerance of Mexican wheat: I. Effect of NO₃ and NaCl on mineral nutrition, growth, grain production of four wheats. *Soil Science Society of America Journal*, 37(5), 711-715.
- Blumenthal, J. M., Baltensperger, D. D., Cassman, K. G., Mason, S. C., and Pavlista, A. D. (2008). Importance and effect of nitrogen on crop quality and health. *Nitrogen in the Environment: Sources, Problems, and Management*, 51-70.
- Bock, B. R. (1984). Efficient use of nitrogen in cropping systems. In: *Nitrogen in Crop Production* (Ed. R.D. Hauck). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wisconsin. pp. 273-294.

- Bolan, N. S., and Hedley, M. J. (2003). Role of carbon, nitrogen, and sulfur cycles in soil acidification. *Handbook of soil acidity*. Marcel Dekker, New York, pp. 29-56.
- Borkakati, K., and Takkar, P. N. (2000). Forms of boron in acid alluvial and lateritic soils in relation to ecosystem and rainfall distribution. In: *Proceedings of International Conference on Managing Resources for Sustainable Agricultural Production in the 21st Century. Better Crops 2*, pp. 127-128.
- Bowen, J. E. (1968). Borate absorption in excised sugarcane leaves. *Plant and Cell Physiology*, 9(3), 467-478.
- Bowen, J. E. (1969). Absorption of borate ionic species by *Saccharum officinarum* L. *Plant and cell physiology*, 10(1), 227-230.
- Bowen, J. E., and Nissen, P. (1977). Boron uptake by excised barley roots, 2: Characteristics and kinetics of active uptake. *Physiologia Plantarum*.
- Boyd, D. C., and Rogers, M. E. (2004). Effect of salinity on the growth of chicory (*Cichorium intybus* cv. Puna)—a potential dairy forage species for irrigation areas. *Animal Production Science*, 44(2), 189-192.
- Bradford, G. R. (1966). Boron. *Diagnostic criteria for plants and soils*, 33-61.
- Bradford, G. R., and Harding, R. B. (1957). A survey of micronutrients in leaves of forty-three high-producing orange orchards in southern California. In: *Proceedings American Society for Horticultural Science*, 70, pp. 252-256.
- Brar, M. S., Sharma, P., Singh, A., and Saandhu, S. S. (2012). Nitrogen use efficiency (NUE), growth, yield parameters and yield of Maize (*Zea mays* L.) as affected by K application. *Electron International Fertiliser Correspondent*, 30, 3-6.
- Brighenti, A. M., and Castro, C. (2008). Boron foliar application on sunflower (*Helianthus annuus* l.) Associated with herbicides/aplicación foliar de boro en girasol (*Helianthus annuus* l.) Asociada a herbicidas/application foliar de bore sur lê tournesol (*Helianthus annuus*) associé aux herbicides. *Helia*, 31(48), 127-136.
- Brinkman, R. (1970). Ferrollysis, a hydromorphic soil forming process. *Geoderma*, 3(3), 199-206.
- Brinkman, R. (1977). Surface-water gley soils in Bangladesh: genesis. *Geoderma*, 17(2), 111-144.
- Broadley, M, Brown, P, Cakmak, I, Rengel, Z. and Zhao, F. (2012). Functions of nutrients: micronutrients. In: Marscher's mineral nutrition of higher plants. (Ed.) Marschner, P. (3rd Edition), Elsevier Ltd, London.
- Brown, J. R. (1987). *Soil testing: sampling, correlation, calibration, and interpretation proceedings of a symposium*. Soil Science Society of America, Madison, Wisconsin.

Brown, P. H., Bellaloui, N., Wimmer, M. A., Bassil, E. S., Ruiz, J., Hu, H., and Römheld, V. (2002). Boron in plant biology. *Plant biology*, 4(02), 205-223.

Brown, P. H. and Hu, H. (1998). Phloem boron mobility in diverse species. *Botanica Acta* 111(4), 331-335

Brown, P. H. and Shelp, B. J. (1997). Boron mobility in plants. *Plant Soil*, 193(1), 85-101.

Brunetti, J. (2003). Benefits of biodiverse forage. *A voice of Eco-agriculture*, 33(10), 7-11.

Bühmann, C., Fey, M. V., and De Villiers, J. M. (1985). Aspects of the X-ray identification of swelling clay minerals in soils and sediments. *South African Journal of Science*, 81(8), 505-509.

Bukhsh, M., Ahmad, R., Iqbal, J., Maqbool, M. M., Ali, A., Ishaque, M., and Hussain, S. (2012). Nutritional and physiological significance of potassium application in maize hybrid crop production. *Pakistan Journal of Nutrition*, 11(2), 187.

Busari, M. A., Salako, F. K., and Adetunji, M. T. (2008). Soil chemical properties and maize yield after application of organic and inorganic amendments to an acidic soil south-western Nigeria. *Spanish Journal of Agricultural Research*, 6(4), 691-699.

Buszewski, B., Kawka, S., Suprynowicz, Z., and Wolski, T. (1993). Simultaneous isolation of rutin and esculin from plant material and drugs using solid-phase extraction. *Journal of Pharmaceutical and Biomedical Analysis* 11(3), 211-215.

Cadalen, T., Mörchen, M., Blassiau, C., Clabaut, A., Scheer, I., Hilbert, J. L., and Quillet, M. C. (2010). Development of SSR markers and construction of a consensus genetic map for chicory (*Cichorium intybus* L.). *Molecular Breeding*, 25(4), 699-722.

Cakmak, I., Kurz, H., and Marschner, H. (1995). Short-term effects of boron, germanium and high light intensity on membrane permeability in boron deficient leaves of sunflower. *Physiologia Plantarum*, 95(1), 11-18.

Campbell, C. (2000). Reference sufficiency ranges for plant analysis in the southern region of the United States.

Canaday, C. H., and Wyatt, J. E. (1992). Effects of nitrogen fertilisation on bacterial soft rot in two broccoli cultivars, one resistant and one susceptible to the disease. *Plant Disease*, 76(10), 989-991.

Carballo, S.J., Blankenship, S.M., Sers, D.C. and Ritchie, D.F. (1994). Drip fertigation with nitrogen and potassium and post-harvest susceptibility to bacterial soft rot of bell peppers. *Journal of Plant Nutrition*, 17, 1175-1191.

Chaignon, V., Bedin, F., and Hinsinger, P. (2002). Copper bioavailability and rhizosphere pH changes as affected by nitrogen supply for tomato and oilseed rape cropped on an acidic and calcareous soil. *Plant and Soil*, 243(2), 219-228.

- Chapman, H. D., and Vanselow, A. P. (1955). Boron deficiency and excess. *Californian Citrograph*, 41, 31-34.
- Chapman, L. S. (1971). Progress in soil test calibration trials. In: *Proceedings of the Queensland Society of Sugar Cane Technologists. 38th Conference* (101), 107.
- Chapman, L. S., Haysom, M. B. C., and Usher, J. F. (1995). Canegrowers accept biodunder as a plant nutrient source at Mackay. *Proceedings of the Australian Society of Sugar Cane Technologists*, 17, 199-206.
- Chaudhary, D. R., Shukla, L. M., and Gupta, A. (2005). Boron equilibria in soil-a review. *Agricultural reviews-agricultural research communications centre India*, 26(4), 288.
- Chauhan, R. P. S., and Asthana, A. K. (1981). Tolerance of lentil, barley and oats to boron in irrigation water. *The Journal of Agricultural Science*, 97(1), 75-78.
- Chhabra, R. (1996). *Soil salinity and water quality*. CRC Press, Boca Raton, Florida.
- Chubey, B. B., and Dorrell, D. G. (1978). Total reducing sugar, fructose and glucose concentrations and root yield of two chicory cultivars as affected by irrigation, fertilizer and harvest dates. *Canadian Journal of Plant Science* 58(3), 789-793.
- Claassen, M. M. (1971). Effect of agricultural limestone on nutrient composition and yield of corn on soil chemical properties. Retrospective Theses and Dissertations. 4872. <http://lib.dr.iastate.edu/rtd/4872>.
- Clay, D. E., Clapp, C. E., Dowdy, R. H., and Molina, J. A. E. (1993). Mineralisation of nitrogen in fertilizer-acidified lime-amended soils. *Biology and Fertility of Soils*, 15(4), 249-252.
- Collins, M., and McCoy, J. E. (1997). Chicory productivity, forage quality, and response to nitrogen fertilisation. *Agronomy Journal*, 89(2), 232-238.
- Cox, A. E., Joern, B. C., Brouder, S. M., and Gao, D. (1999). Plant-available potassium assessment with a modified sodium tetraphenylboron method. *Soil Science Society of America Journal*, 63(4), 902-911.
- Crush, J. R., and Evans, J. P. M. (1990). Shoot growth and herbage element concentrations of 'Grasslands Puna' chicory (*Cichorium intybus* L.) under varying soil pH. In: *Proceedings of the New Zealand Grassland Association* 51, pp. 163-166.
- Ćustić, M., Horvatić, M., and Butorac, A. (2002). Effects of nitrogen fertilization upon the content of essential amino acids in head chicory (*Cichorium intybus* L. var. foliosum). *Scientia Horticulturae*, 92(3), 205-215.
- Ćustić, M., Poljak, M., Čoga, L., Ćosić, T., Toth, N., and Pecina, M. (2003). The influence of organic and mineral fertilisation on nutrient status, nitrate accumulation, and yield of head chicory. *Plant, Soil and Environment*, 49(5), 218-222.

Cutcliffe, J. A., and Gupta, U. C. (1980). Effects of added nitrogen, phosphorus, and potassium on leaf tissue boron concentration of three vegetable crops. *Canadian Journal of Plant Science*, 60(2), 571-576.

D'Egidio, M.G., Cecchini, C., Cervigni, T., Donini, B., and Pignatelli, V. (1998). Production of fructose from cereal stems and polyannual cultures of Jerusalem artichoke. *Industrial Crops and Products* 7, 113-119.

Dakora, F. D., and Phillips, D. A. (2002). Root exudates as mediators of mineral acquisition in low-nutrient environments. *Plant and Soil*, 245(1), 35-47.

Day, P. R. (1965). Pipette method of particle size analysis. In: Black, C.A. (Ed.), *Methods of soil analysis. Part I*. ASA, Madison, WI, 553-562.

Dell, B. and Huang, L. B. (1997). Physiological response of plants to low boron. *Plant and Soil* 193(1-2), 103-120.

Department for Environment, Food and Rural Affairs (DEFRA). (2010). *Fertiliser Manual RB 209* 8th ed. TSO, Norwich, U.K.

Department of Agriculture, Forestry and Fisheries (DAFF). (2013). Abstract of agricultural statistics. [Online]. Available at: www.nda.agri.za/docs/statsinfo/Ab2013.pdf. Accessed on 22/6/17.

Department of Mineral and Energy Affairs, (1988). Dundee 2830, 1: 250 000 geological map series. Geological Survey, Pretoria: Government Printer.

DeTurk, E. E., and Olson, L. C. (1941). Determination of boron in some soils of Illinois and Georgia. *Soil Science*, 52(5), 351-358.

Dhliwayo, D.K.C., Sithole, T. and Nemasasi, H. (1998). Soil acidity – Is it a problem in maize-based production systems of the communal areas of Zimbabwe? In: *Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe*. Waddington, S.R., Murwira, H.K., Kumwenda, J.D.T., Hikwa, D. and Tagwira, F. (Eds), Soil Fertility Network and CIMMYT – Zimbabwe, Harare, Zimbabwe pp. 217-221.

Dible, W. T., and Berger, K. C. (1952). Boron content of alfalfa as influenced by boron supply. *Soil Science Society of America Journal*, 16(1), 60-62.

Dobermann, A., Cruz, P. S., and Cassman, K. G. (1996). Fertiliser inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems. I. Potassium uptake and K balance. *Nutrient Cycling in Agroecosystems*, 46(1), 1-10.

Doida, A.M. (1977). Effect of different dates of sowing and various nitrogen levels on growth yield of chicory. M.Sc. (Agri.) thesis, Gujarat Agricultural University, Sardarkrushinagar, India.

Dordas, C. (2006). Foliar boron application improves seed set, seed yield, and seed quality of alfalfa. *Agronomy Journal*, 98(4), 907-913.

Dregne, H. E., and Powers, W. L. (1942). Boron fertilisation of alfalfa and other legumes in Oregon. *Journal of the American Society of Agronomy*, 34, 902-912.

Drinkwater, L. E., Cambardella, C. A., Reeder, J. D., Rice, C. W., Doran, J. W., and Jones, A. J. (1996). Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: *Methods for Assessing Soil Quality* (Eds J.W. Doran and A.J. Jones), Special Publication 49, Soil Science Society of America, Madison, Wisconsin. pp. 217-229.

Druart, N., De Roover, J., Van den Ende, W., Goupil, P., Van Laere, A., and Rambour, S. (2001). Sucrose assimilation during early developmental stages of chicory (*Chicorium intybus* L.) plants. *Planta* 212(3), 436-443.

Dugger, W. M. (1983). Boron in plant metabolism. *Encyclopedia of plant physiology. New Series*.

Dunn, D., Stevens, G., and Kendig, A. (2005). Boron fertilization of rice with soil and foliar applications. *Crop Management*, 4(1), 1-10.

Eaton, F. M. (1935). Boron in soils and irrigation waters and its effect on plants, with particular reference to the San Joaquin Valley of California (No. 164477). United States Department of Agriculture, Economic Research Service.

Eaton, F. M. (1944). Deficiency, toxicity and accumulation of boron in plants (No. REP-482. CIMMYT.).

Edwards, D. (1967). A plant ecology survey of the Tugela River basin, Natal. Memoir 36, Botanical Survey, South Africa. Natal: Town and Regional Planning Commission.

Elrashidi, M. A., and O'Connor, G. A. (1982). Boron sorption and desorption in soils. *Soil Science Society of America Journal*, 46(1), 27-31.

El-Sheikh, A. M., and Ulrich, A. (1970). Interactions of rubidium, sodium, and potassium on the nutrition of sugar beet plants. *Plant Physiology* 46(5), 645-649.

Engels, C., and Kirkby, E. A. (2001). Cycling of nitrogen and potassium between shoots and roots in maize as affected by shoot and root growth. *Journal of Plant Nutrition and Soil Science*, 164(2), 183-191.

Epstein E., and Bloom A.J. (2005). Mineral nutrition of plants: principles and perspectives, 2nd edn. Sinauer Associates, Inc Publishers, Sunderland.

European Food Safety Authority (EFSA). (2012). Update on acrylamide levels in food from monitoring years 2007 to 2010. *EFSA Journal* 10, 1-38.

European Medicines Agency, (2013). Assessment report on *Cichorium intybus* L., [Online]. Available at:

http://www.ema.europa.eu/docs/en_GB/document_library/Herbal_-_HMPC_assessment_report/2013/03/WC500140398.pdf. Accessed on 22/6/17.

Eurostat, (2012). Europe in figures. Eurostat yearbook 2012. European Union 2012, Belgium.

- Evans, C. E., and Attoe, O. J. (1948). Potassium-supplying power of virgin and cropped soils. *Soil Science*, 66(5), 323-334.
- Evans, L. J. (1987). Retention of boron by agricultural soils from Ontario. *Canadian Journal of Soil Science*, 67(1), 33-42.
- Evans, P. S. (1978). Plant root distribution and water use patterns of some pasture and crop species. *New Zealand Journal of Agricultural Research*, 21(2), 261-265.
- Fageria, N. K. (1983). Ionic interactions in rice plants from dilute solutions. *Plant and Soil*, 70(3), 309-316.
- Fageria, N. K., and Baligar, V. C. (2008). Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. *Advances in Agronomy* 99, 345-399.
- Fageria, N. K., Baligar, V. C., and Jones, C. A. (2010). *Growth and mineral nutrition of field crops*. CRC Press.
- Fageria, V. D. (2001). Nutrient interactions in crop plants. *Journal of Plant Nutrition*, 24(8), 1269-1290.
- FAOSTAT. (2013). Agriculture Organization of the United Nations. [Online]. Available at: <http://faostat3.fao.org/download/Q/QC/E>. Accessed on 8/2/2016.
- Farina, M. P. W. (1981). *The Hunter system of soil analysis*. Department of Agriculture, South Africa.
- Farina, M. P. W., and Channon, P. (1991). A field comparison of lime requirement indices for maize. *Plant and Soil*, 134(1), 127-135.
- Farina, M. P. W., Channon, P., Thibaud, G. R., and Phipson, J. D. (1992). Soil and plant potassium optima for maize on a kaolinitic clay soil. *South African Journal of Plant and Soil*, 9(4), 193-200.
- Farina, M. P. W., Manson, A. D., and Johnston, M. A. (1993). Fertiliser guidelines. *Maize in Natal*, 6.
- Feller, C., and Fink, M. (2002). Nmin. target values for field vegetables. *Acta Horticulture* 571, 195-201.
- Fergus, I. F., and Martin, A. E. (1974). Studies on potassium. IV. Interspecific differences in the uptake of non-exchangeable potassium. *Soil Research*, 12(2), 147-158.
- Fleischer, A., O'Neill, M. A., and Ehwald, R. (1999). The pore size of non-graminaceous plant cell walls is rapidly decreased by borate ester cross-linking of the pectic polysaccharide rhamnogalacturonan II. *Plant Physiology*, 121(3), 829-838.
- Fleming, G. A. (1980). Essential micronutrients. I. Boron and molybdenum. *Applied Soil Trace Elements*. (Ed.) B. E. Davies.

- Forde, B. G. (2002). The role of long-distance signalling in plant responses to nitrate and other nutrients. *Journal of Experimental Botany*, 53(366), 39-43.
- Foth, H. D. (2003). Fundamentals of soil science. (8th ed.) John Wiley and Sons. New York.
- Fox, R. H. (1968). The effect of calcium and pH on boron uptake from high concentrations of boron by cotton alfalfa. *Soil Science*, 106(6), 435-439.
- Foy, C. D., Chaney, R. T., and White, M. C. (1978). The physiology of metal toxicity in plants. *Annual Review of Plant Physiology*, 29(1), 511-566.
- Freundlich, H. M. F. (1906). Over the adsorption in solution. *Journal of Physical Chemistry*, 57(385), e470.
- Fu, M. H., Xu, X. C., and Tabatabai, M. A. (1987). Effect of pH on nitrogen mineralisation in crop-residue-treated soils. *Biology and Fertility of Soils*, 5(2), 115-119.
- Gaines, T. P., and Mitchell, G. A. (1979). Chemical methods for soil and plant analysis. *Agronomy Handbook*, (1).
- Gee, G. W., and Bauder, J. W. (1986). Particle-size analysis. *Methods of soil analysis: Part 1. Physical and mineralogical methods*, 383-411.
- Gentile, R.M. (2003). Forages for soil improvement in Uruguayan cropping systems. MSc thesis, Department of Plant Science, University of Manitoba, Winnipeg.
- Gestring, W. D., and Soltanpour, P. N. (1987). Comparison of soil tests for assessing boron toxicity to alfalfa. *Soil Science Society of America Journal*, 51(5), 1214-1219.
- Gething, P. A. (1993). Improving returns from nitrogen fertiliser. The potassium-nitrogen partnership. *Research Topics-International Potash Institute*, (No.13, 2nd revision).
- Gill, N. T., Barnard, D. J., and Vear, K. C. (1980). *Dicotyledonous crops*. Duckworth.
- Goldbach, H. E. (1997). A critical review on current hypotheses concerning the role of boron in higher plants: suggestions for further research and methodological requirements. *Journal of Trace and Microprobe Techniques*, 15(1), 51-91.
- Goldbach, H. E., and Wimmer, M. A. (2007). Boron in plants and animals: Is there a role beyond cell-wall structure? *Journal of Plant Nutrition and Soil Science*, 170(1), 39-48.
- Goldberg, S. (1997). Reactions of boron with soils. *Plant and Soil*, 193(1), 35-48.
- Goldberg, S., and Forster, H. S. (1991). Boron sorption on calcareous soils and reference calcites. *Soil Science*, 152(4), 304-310.
- Goldberg, S., Forster, H. S., and Heick, E. L. (1993). Boron adsorption mechanisms on oxides, clay minerals, and soils inferred from ionic strength effects. *Soil Science Society of America Journal*, 57(3), 704-708.

- Goldberg, S., Tabatabai, M. A., Sparks, D. L., Al-Amoodi, L., and Dick, W. A. (2005). Equations and models describing adsorption processes in soils. *Soil Science Society of America Book Series*, 8, 489.
- Gomez, K. A., and Gomez, A. A. (1984). Statistical procedures for agricultural research. John Wiley and Sons.
- Gothing, P.A. (1962). Soil potassium: A review of some recent investigations. Potash Review Subject 16, 22nd Suite, pp. 1-10.
- Govindaraju, K. (1994). 1994 compilation of working values and sample description for 383 geostands. *Geostands newsletter*, 18(S1), 1-158.
- Greenwood, D. J., Cleaver, T. J., Turner, M. K., Hunt, J., Niendorf, K. B., and Loquens, S. M. H. (1980a). Comparison of the effects of potassium fertilizer on the yield, potassium content and quality of 22 different vegetable and agricultural crops. *The Journal of Agricultural Science* 95(02), 441-456.
- Greenwood, D. J., Cleaver, T. J., Turner, M. K., Hunt, J., Niendorf, K. B., and Loquens, S. M. H. (1980b). Comparison of the effects of phosphate fertilizer on the yield, phosphate content and quality of 22 different vegetable and agricultural crops. *The Journal of Agricultural Science* 95(02), 457-469.
- Greenwood, D. J., Cleaver, T. J., Turner, M. K., Hunt, J., Niendorf, K. B., and Loquens, S. M. H. (1980c). Comparison of the effects of nitrogen fertilizer on the yield, nitrogen content and quality of 21 different vegetable and agricultural crops. *The Journal of Agricultural Science*, 95(02), 471-485.
- Greyling, L. (2010). Revitalising local chicory. *Farmers Weekly South Africa* (issue 10) December 2010. [Online]. Available at: <http://www.farmersweekly.co.za/article.aspx?id=5568&dh=Revitalising-local-chicory>. Accessed 8/2/2016.
- Grunes, D. L., Huang, J. W., Smith, F. W., Joo, P. K., and Hewes, D. A. (1992). Potassium effects on minerals organic acids in three cool-season grasses. *Journal of Plant Nutrition*, 15(6-7), 1007-1025.
- Grunes, D. L., Stout, P. R., and Brownell, J. R. (1970). Grass tetany of ruminants. *Advances in Agronomy*, 22, 331-374.
- Gupta, U. C. (1968). Relationship of total and hot-water soluble boron, and fixation of added boron, to properties of podzol soils. *Soil Science Society of America Journal*, 32(1), 45-48.
- Gupta, U. C. (1972). Interaction effects of boron and lime on barley. *Soil Science Society of America Journal*, 36(2), 332-334.
- Gupta, U. C. (1980). Boron nutrition of crops. *Advances in Agronomy*, 31, 273-307.

Gupta, U. C. (1984). Boron nutrition of alfalfa, red clover, and timothy grown on podzol soils of eastern Canada. *Soil Science*, 137(1), 16-22.

Gupta, U. C. (1993). Boron and its role in crop production. CRC Press, Boca Raton, FL.

Gupta, U. C., and Cutcliffe, J. A. (1971). Determination of optimum levels of boron in rutabaga leaf tissue and soil. *Soil Science*, 111(6), 382-385.

Gupta, U. C., and Cutcliffe, J. A. (1972). Effects of lime and boron on brown-heart, leaf tissue calcium/boron ratios, and boron concentrations of rutabaga. *Soil Science Society of America Journal*, 36(6), 936-939.

Gupta, U. C., and Cutcliffe, J. A. (1973). Boron nutrition of broccoli, brussel sprouts, and cauliflower grown on Prince Edward Island soils. *Canadian Journal of Soil Science*, 53(3), 275-279.

Gupta, U. C., and Cutcliffe, J. A. (1978). Effects of methods of boron application on leaf tissue concentration of boron and control of brown-heart in rutabaga. *Canadian Journal of Plant Science*, 58(1), 63-68.

Gupta, U. C., and Cutcliffe, J. A. (1985). Boron nutrition of carrots and table beets grown in a boron deficient soil 1. *Communications in Soil Science and Plant Analysis*, 16(5), 509-516.

Gupta, U. C., Jame, Y. W., Campbell, C. A., Leyshon, A. J., and Nicholaichuk, W. (1985). Boron toxicity and deficiency: a review. *Canadian Journal of Soil Science*, 65(3), 381-409.

Gupta, U. C., Sterling, J. D. E., and Nass, H. G. (1973). Influence of various rates of compost and nitrogen on the boron toxicity symptoms in barley and wheat. *Canadian Journal of Plant Science*, 53(3), 451-456.

Haak, E. (1978). [Studies on cereal root development and mineral uptake, B: Uptake of calcium, phosphorus and potassium from the plough layer and the subsoil-field experiments [barley, oats, wheat], Sweden]. *Rapport-Sveriges Lantbruksuniversitet, Institutionen foer Radiobiologi (Sweden)*.

Hadas, A., and Hagin, J. (1972). Boron adsorption by soils as influenced by potassium. *Soil Science*, 113(3), 189-193.

Hafner, S., and Kuzyakov, Y. (2016). Carbon input and partitioning in subsoil by chicory and alfalfa. *Plant and Soil*, 1-14.

Hagin, J., Olsen, S. R., and Shaviv, A. (1990). Review of interaction of ammonium-nitrate and potassium nutrition of crops. *Journal of Plant Nutrition*, 13(10), 1211-1226.

Hamence, J. H., and Oram, P. A. (1964). Effects of soil and foliar applications of sodium borate to sugar beet. *Journal of the Science of Food and Agriculture*, 15(8), 565-579.

Hannan, A., Ranjha, A. M., Waqas, M., and Niaz, A. (2007). Potassium adsorption characteristics of four different textured alkaline calcareous soils. *Pakistan Journal of Agricultural Sciences (Pakistan)*.

Hannan, J. M. (2011). *Potassium-magnesium antagonism in high magnesium vineyard soils*. Thesis, Iowa State University, Ames, IA 50011, USA.

Hannaway, D. B., Bush, L. P., and Leggett, J. E. (1982). Mineral composition of Kenhy tall fescue as affected by nutrient solution concentrations of Mg and K. *Journal of Plant Nutrition*, 5(3), 137-151.

Hara, T., and Tamai, M. (1968). Some factors affecting behaviour of boron in soil: I. Some Soil Properties Affecting Boron Adsorption of Soil. *Soil Science and Plant Nutrition*, 14(6), 215-224.

Harrison, H. C., and Bergman, E. L. (1981). Calcium, magnesium, and potassium interrelationships affecting cabbage production [Mineral antagonisms]. *Journal American Society for Horticultural Science*.

Hartemink, A.E., and Sonneveld, M.P.W. (2013). Soil maps of The Netherlands. *Geoderma*, 204, 1-9.

Havlin, J. L., Beaton, J. D., Nelson, W. L., and Tisdale, S. L. (2005). Soil fertility and fertilizers: An introduction to nutrient management (Vol. 515). Upper Saddle River, NJ: Pearson Prentice Hall.

Hawkesford, M., Horst, W, Kichey, T, Lambers, H, Schjoerring, J, Skrumsager Moller, I and White, P. (2012). Functions of macronutrients. In: Marscher's mineral nutrition of higher plants. (Ed.) Marschner, P. (3rd Edition), Elsevier Ltd, London.

Hay, R. K. M. (1995). Harvest index: a review of its use in plant breeding and crop physiology. *Annals of Applied Biology*, 126(1), 197-216.

Haynes, R.J. (1982). Effect of liming on phosphate availability in acid soils. *Plant and Soil*, 68(3), 289-308.

Haynes, R.J. (1990). Active ion uptake and maintenance of cation-anion balance: A critical examination of their role in regulating rhizosphere pH. *Plant and Soil*, 126, 247-264.

Haysom M.B. (1971). The estimation of potassium availability in Mackay soils. *Proceedings of the Queensland Society of Sugarcane Technologists* 38:113-119.

Heck, R. J., Tiessen, H., Salcedo, I. H., and Santos, M. C. (2003). Soil chemical changes under irrigated mango production in the Central Sao Francisco River Valley, Brazil. *Journal of Environmental Quality*, 32(4), 1414-1421.

Heenan, D. P., and Campbell, L. C. (1981). Influence of potassium and manganese on growth and uptake of magnesium by soybeans (*Glycine max* (L.) Merr. cv. Bragg). *Plant and Soil*, 61(3), 447-456.

Herrera-Estrella, L. (1999). Transgenic plants for tropical regions: some considerations about their development and their transfer to the small farmer. *Proceedings of the National Academy of Sciences* 96(11), 5978-5981.

Hetrick, J. A., and Schwab, A. P. (1992). Changes in aluminum and phosphorus solubilities in response to long-term fertilisation. *Soil Science Society of America Journal*, 56(3), 755-761.

Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant and Soil*, 237(2), 173-195.

Hinsinger P. (2002) Potassium. In: Lal R (Ed) Encyclopedia of soil science. Marcel Dekker Inc., New York.

Hinsinger, P., Plassard, C., Tang, C., and Jaillard, B. (2003). Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: a review. *Plant and Soil*, 248(1-2), 43-59.

Hochmuth, G.J., Hanlon, E., Snyder, G., Nagata, R., and Schueneman, T. (2009). Fertilization of sweet corn, celery, romaine, escarole, endive, and radish on organic soils in Florida. *University of Florida IFAS Extension, BUL313 document*.

Hochmuth, G. J., Hochmuth, R. C., Donley, M. E., and Hanlon, E. A. (1993). Eggplant yield in response to potassium fertilisation on sandy soil. *Horticultural Science*, 28(10), 1002-1005.

Hochmuth, G.J., Maynard, D., Vavrina, C., Hanlon, E., and Simonne, E. (1991). Plant tissue analysis and interpretation for vegetable crops in Florida. *Gainesville, FL: Florida Cooperative Extension Service SS-VEC-42*.

Hodgkiss, W. S., Hageman, R. H., and McHargue, J. S. (1942). The amount of boron absorbed by soybean plants and its effect on their growth. *Plant Physiology*, 17(4), 652.

Hoover, C. D., Jones, U. S., and Gholston, L. E. (1948). Release of nonexchangeable potassium as influenced by weathering, soil mineral type, soil reaction, and potassium fertilization. In: *Soil Science Society of America. Proceedings 31* (Vol. 13, pp. 347-51).

Howeler, R. H., Flor, C. A., and Gonzalez, C. A. (1978). Diagnosis and correction of B deficiency in beans mungbeans in a mollisol from the Cauca Valley of Colombia. *Agronomy Journal*, 70(3), 493-497.

Hu, H. and Brown, P.H. (1994). Localization of boron in cell walls of squash and tobacco and its association with pectin. *Plant Physiology*, 105(2), 681-689.

Hu, H., and Brown, P. H. (1997). Absorption of boron by plant roots. *Plant and Soil*, 193(1), 49-58.

Huber, D. M., and Jones, J. B. (2013). The role of magnesium in plant disease. *Plant and Soil*, 368(1-2), 73-85.

Hunter, A. H. (1974). International soil fertility evaluation and improvement: laboratory procedures. *Department of Soil Science, North Carolina State University, Raleigh, NC*.

Hunter, A. H. (1975). [New techniques and equipment for routine soil-plant analytical procedures]. In 2. *Seminario sobre Manejo de Suelos y el Proceso de Desarrollo en America Tropical, Cali (Colombia), 10 Feb 1974*.

Interactive European Network for Industrial Crops and their Applications (IENICA). (2003). Report from the State of Belgium. Gembloux Agricultural University, Belgium.

Ishizuka, Y., and Tanaka, A. (1960). The inorganic nutrition of rice plants. IV. Effect of calcium, magnesium and sulphur level of the culture solutions on the yield and chemical composition of plants. *Journal of the Science of Soil*, 30, 414-416.

Jakobsen, S. T. (1993). Interaction between plant nutrients: III. Antagonism between potassium, magnesium and calcium. *Acta Agriculturae Scandinavica B-Plant Soil Sciences*, 43(1), 1-5.

Jarrel, W.M. and Beverly, R.B. (1981). The dilution effect in plant nutrition. *Advances in Agronomy*, 34, 197-224.

Jennings, K., Roux, P. L., Huyssteen, C. V., Hensley, M., and Zere, T. B. (2008). Redox conditions related to interflow in a soil of the Kroonstad form in the Weatherley catchment. *South African Journal of Plant and Soil*, 25(4), 204-213.

Johnston, A. E., and Goulding, K. W. T. (1990). The use of plant and soil analyses to predict the potassium supplying capacity of soil. In: *Development of K-fertilizer recommendations. Proceedings of the 22nd Colloquium of the International Potash Institute, International Potash Institute Bern Switzerland* (pp. 177-204).

Johnston, A. E., and Goulding, K. W. T. (1992). Potassium concentrations in surface and ground waters and the loss of potassium in relation to land use. In: *The 23rd Colloquium of the International Potash Institute* (pp. 135-158).

Johnston, M. A., Miles, N., and Thibaud, G. R. (1991). Quantities of phosphorus fertilizer required to raise the soil test value. *South African Journal of Plant and Soil* 8(1), 17-21.

Johnston, M. A., Miles, N., Thibaud, G. R., and Hughes, J. C. (1999). Quantities of potassium fertiliser required to raise soil test value. *Communications in Soil Science and Plant Analysis*, 30(17-18), 2485-2487.

Jones, H. E., and Scarseth, G. D. (1944). The calcium-boron balance in plants as related to boron needs. *Soil Science*, 57(1), 15-24.

Judžentienė, A., and Būdienė, J. (2008). Volatile constituents from aerial parts and roots of *Cichorium intybus* L.(chicory) grown in Lithuania. *Chemija*, 19(2), 25-28.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., and Schuman, G. E. (1997). Soil quality: a concept, definition, and framework for evaluation (a guest editorial). *Soil Science Society of America Journal* 61(1), 4-10.

- Kawasaki, T. (1995). Metabolism physiology of calcium and magnesium. In: Science of the rice plant; Matsuo, T., Kumazawa, K., Ishii, R., Ishihara, K., and Hirata, H., (Eds.), Food Agricultural Policy Research Center, Tokyo, Japan, Vol. 2, 412-419.
- Kenyan, O., Mbuvi, H. M., Muthengia, J. M., and Omayo, E. K. (2014). Use of adsorption isotherm models to determine potassium fertilizer acreage doses for optimum maize growth and yields in Nyamira County, Kenya. *International Journal of Agriculture and Crop Sciences*, 7(15), 1525.
- Keren, R., Bingham, F. T., and Rhoades, J. D. (1985). Effect of clay content in soil on boron uptake and yield of wheat. *Soil Science Society of America Journal*, 49(6), 1466-1470.
- Khaghani, S., Shakouri, M. J., Mafakheri, S., and Aslanpour, M. (2012). Effect of different chemical fertilizers on chicory (*Cichorium intybus* L.). *Indian Journal of Science and Technology* 5(1), 1933-1935.
- Khan, S. A., Mulvaney, R. L., and Ellsworth, T. R. (2014). The potassium paradox: Implications for soil fertility, crop production and human health. *Renewable Agriculture and Food Systems*, 29(1), 3-27.
- Koch, J. T., Orchard, E. R., and Sumner, M. E. (1970). Leaf composition and yield response of corn in relation to quantity-intensity parameters for potassium. *Soil Science Society of America Journal*, 34(1), 94-98.
- Kohl Jr, H. C., and Oertli, J. J. (1961). Distribution of boron in leaves. *Plant Physiology*, 36(4), 420.
- Krauskopf, K. B., Mortvedt, J. J., Giordano, P. M., and Lindsay, W. L. (1972). Micronutrients in agriculture. In: Proceedings of a Symposium. Madison, Wisconsin. (Mortvedt, JJ, Giordano, PC, Lindsay, WL, Eds.), *Soil Science Society of America, Incorporated*, 7-40.
- Kuhlmann, H. (1990). Importance of the subsoil for the K nutrition of crops. *Plant and Soil*, 127(1), 129-136.
- Kurvits, A., and Kirkby, E. A. (1980). The uptake of nutrients by sunflower plants (*Helianthus annuus*) growing in a continuous flowing culture system, supplied with nitrate or ammonium as nitrogen source. *Journal of Plant Nutrition and Soil Science*, 143(2), 140-149.
- Labanauskas, C. K., Jones, W. W., and Embleton, T. W. (1959). Seasonal changes in concentrations of micronutrients (zinc, copper, boron, manganese, and iron) in leaves of Washington Navel orange. In: *Proceedings of the American Society of Horticultural Science*, 74, 300-307.
- Łachowski, J. (1962). Results of experiments on mineral fertilization of two chicory varieties. *Rocz Nauk Rolniczych Ser A Roslinna*, 145-162.
- Land Type Survey Staff, (1986a). Land types of the map 2730 Vryheid (Ed. C.N. MacVicar) *Memoirs of the Agricultural Natural Resources of South Africa*. No.7.

- Land Type Survey Staff, (1986b). Land types of the map 2830 Richards Bay (Ed. C.N. MacVicar) Memoirs of the Agricultural Natural Resources of South Africa. No.11.
- Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical Society*, 40(9), 1361-1403.
- Le Roux, J., and Sumner, M. E. (1968). Labile potassium in soils I: Factors affecting the quantity-intensity (q/i) parameters. *Soil Science*, 106(1), 35-41.
- Le Roux, P.A.L., du Preez, C.C. and Böhmann, C. (2005). Indications of ferrollysis and structure degradation in an Estcourt soil and possible relationships with plinthite formation. *South African Journal of Plant and Soil*, 22(4), 199-206.
- Lecourieux, D., Ranjeva, R., and Pugin, A. (2006). Calcium in plant defence-signalling pathways. *New Phytologist*, 171(2), 249-269.
- Ledgard, S. F., and Saunders, W. M. H. (1982). Effects of nitrogen fertiliser and urine on pasture performance and the influence of soil phosphorus and potassium status. *New Zealand Journal of Agricultural Research*, 25(4), 541-547.
- Lee, R., and Metson, A. J. (1977). Potassium removal from soil by lucerne over three years and the effect of potassium topdressing. *New Zealand Journal of Agricultural Research*, 20(2), 185-192.
- Lee-Steere, P., Ostatek-Boczynski, Z.A. and Joyce, P. (2014). Microwave method for the determination of nitric acid extractable potassium in sugarcane soils. *Proceedings of the Australian Society of Sugarcane Technologists*. 36.
- Li, B.H., Li, W.H., Kui, M.C., Chao, W.S., Jern, H.P., Li, C.R., Chu, W.J. and Wang, C.L. (1978). Studies on the cause of sterility of wheat. *Journal Northeast Agricultural College*, 3, 1-19.
- Li, L., Tang, C., Rengel, Z., and Zhang, F. S. (2004). Calcium, magnesium and microelement uptake as affected by phosphorus sources and interspecific root interactions between wheat and chickpea. *Plant and Soil*, 261(1), 29-37.
- Liang, M, Lin, M., Lin, Z, Zhao, L., Zhao, G., Li, Q., and Yin, X. (2015). Identification, functional characterization, and expression pattern of NaCl-inducible vacuolar Na⁺/H⁺ antiporter in chicory (*Cichorium intybus* L.). *Plant Growth Regulation* 75(3), 605-614.
- Liebhardt, W. C., Svec, L. V., and Teel, M. R. (1976). Yield of corn as affected by potassium on a coastal plain soil 1. *Communications in Soil Science and Plant Analysis*, 7(3), 265-277.
- Limami, A., and Fiala, V. (1993). Fructan polymerization and depolymerization during the growth of chicory (*Cichorium intybus* L.) plants. *Studies in Plant Science* 3, 191-197.
- Limami, A., and Laville, J. (1991). Agronomie et physiologie. *L'endive, guide pratique*, 123-144.

- Lindemann, Y., Guiraud, G., Chabouis, C., Christmann, J., and Mariotti, A. (1983). Cinq années d'utilisation de l'isotope 15 de l'azote sur betteraves sucrières en plein champ. In: *Proceedings Symposium Nitrogen and Sugar beet* (pp. 99-115).
- Lindsay, W.L. (1973). Inorganic phase equilibria of micronutrients in soils. P. 41-57. In: J.J. Mortvedt, M. Giordano, and W.L. Lindsay (Eds.) *Micronutrients in agriculture*. Soil Science Society of America, Madison, Wisconsin.
- Lipworth, L., Sonderman, J. S., Tarone, R. E., and McLaughlin, J. K. (2012). Review of epidemiologic studies of dietary acrylamide intake and the risk of cancer. *European Journal of Cancer Prevention* 21(4), 375-386.
- Liu, Y. J., Laird, D. A., and Barak, P. (1997). Release and fixation of ammonium and potassium under long-term fertility management. *Soil Science Society of America Journal*, 61(1), 310-314.
- Loaëc, G., Niquet-Léridon, C., Henry, N., Jacolot, P., Volpoet, G., Goudemand, E., Janssens, M., Hance, P., Cadalen, T., Hilbert, J-L., Desprey, B., and Tessier, F.J. (2014). Effects of variety, agronomic factors, and drying on the amount of free asparagine and crude protein in chicory. Correlation with the acrylamide formation during roasting. *Food Research International* 63, 299-305.
- Löfkvist, J., Whalley, W.R. and Clark, L.J. (2005). A rapid screening method for good root penetration ability: Comparison of species with very different root morphology. *Acta Agriculturae Scandinavica, Section B- Soil and Plant Science* 55(2) 120-124.
- Lorenz, H.P., (1989). Ordnungsgemäße Stickstoffversorgung im Freiland-Gemüsebau nach dem "Kulturbegleitenden Nmin-Sollwerte-(KNS)-System": KNS-Daten für 38 Gemüsearten-145 Anbauverfahren. Verein Ehemaliger Gartenbauschüler.
- MacKay, D. C., and Russell, J. S. (1975). Rates of growth, potassium uptake, and changes in the potassium properties of four Queensland soils during intensive cropping by buffel grass, *Cenchrus ciliaris*. *Soil Research*, 13(2), 217-233.
- Mahler, R. L., and McDole, R. E. (1981). Essential plant micronutrients: Boron in Idaho. *University of Idaho Current Information Series*, (608).
- Manson, A. D. (1994). Using the Cedara recommendations to decide which N, P and K fertilisers to use. Cedara Report No. N/A/94/96. Cedara Agricultural Development Institute.
- Manson, A. D. (1997). Using extractable acidity and acid saturation to make lime recommendations in KwaZulu-Natal [South Africa]. In: *Soil Acidity Initiative Symposium, Ermelo (South Africa), 7-9 May 1997*. Soil Acidity Initiative Symposium Steering Committee.
- Manson, A. D. (2000). Sodium, cation exchange and crop response in acid KwaZulu-Natal soils (Doctoral dissertation, University of Natal, Pietermaritzburg).

Manson, A. D., and Katusic, V. (2008). Potato Fertilisation in KwaZulu-Natal. Cedara reports and publications. Cedara Report No. N/A/97/24. Also available at http://agriculture.kzntl.gov.za/portal/publications/cedara_reports_list/cedara_reports/1997/potato_fertilisation.htm.

Manson, A.D., Miles, N., and Farina, M.P.W. (2012). The Cedara computerized fertilizer advisory service (FertRec): Explanatory notes and crop and soil norms. KwaZulu-Natal Department of Agriculture and Environmental Affairs, Pietermaritzburg, South Africa.

Manson, A.D. and Roberts, V.G., (2001). Analytical methods used by the Soil Fertility and Analytical Services Section. KZN Agri-Report No. N/A/2001/04. KwaZulu-Natal Department of Agriculture and Environmental Affairs, Pietermaritzburg, South Africa.

Maqubela, M. P., Mnkeni, P. N. S., Issa, O. M., Pardo, M. T., and D'Acqui, L. P. (2009). Nostoc cyanobacterial inoculation in South African agricultural soils enhances soil structure, fertility, and maize growth. *Plant and Soil* 315(1-2), 79-92.

Marinussen, M., van Kernebeek, H., Broekema, R., Groen, E., Kool, A., van Zeist, W. J., Dolman, M., and Blonk, H. (2012). LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilisation: Cultivation of roots and tubers. [Online]. Available at: <http://blonkconsultants.nl/upload/pdf/PDV%20rapporten/Cultitvation%20roots%20%20tubers%20D02.pdf>. Accessed on 8/2/2016.

Marle, M., and Roux, L. (1991). De voedingsoplossing voor het forceren van witloof. *XIde Tweejaarlijkse internationale witloofdagen, Arras, France*, 89-99.

Marsh, R. P., and Shive, J. W. (1941). Boron as a factor in the calcium metabolism of the corn plant. *Soil Science*, 51(2), 141-152.

Martens, D. C., and Westermann, D. T. (1991). Fertiliser application for correcting micronutrient deficiencies.

Martin, H. W., and Sparks, D. L. (1985). On the behaviour of nonexchangeable potassium in soils 1. *Communications in Soil Science and Plant Analysis*, 16(2), 133-162.

MBB Consulting Engineers, (2016). Feasibility study and business modelling for the production and processing of chicory in Weenen. Dorpspruit, Pietermaritzburg.

McAinsh, M. R., and Pittman, J. K. (2009). Shaping the calcium signature. *New Phytologist*, 181(2), 275-294.

McClung, A. C., and Lott, W. L. (1956). A survey of the nutrient composition of leaf samples from North Carolina peach orchards. *Soil Science Society of America Journal*, 20(1), 10-15.

McGahan, D. G., R. J. Southard, and R.J. Zasoski. (2014). Rhizosphere effects on soil solution composition and mineral stability. *Geoderma* 226, 340-347.

McGuire, R. G., and Kelman, A. (1986). Calcium in potato tuber cell walls in relation to tissue maceration by *Erwinia carotovora* pv. *atroseptica*. *Phytopathology*, 76(4), 401-406.

- Meijer, W. J. M., and Mathijssen, E. W. J. M. (1992). Experimental and simulated production of inulin by chicory and Jerusalem artichoke. *Industrial Crops and Products*, 1(2), 175-183.
- Mengel, K. (1980). A consideration of factors which affect the potassium requirements of various crops. *Potassium Requirements of Crops*, 5.
- Mengel, K., and Dou, H. (1998). Release of potassium from the silt and sand fraction of loess-derived soils. *Soil Science*, 163(10), 805-813.
- Mengel, K., and Kirkby, E. A. (2012). Principles of plant nutrition. Springer Science and Business Media.
- Metson, A. J. (1968). Long-term potassium-supplying power of New Zealand soils. *International Society of Soil Science Transactions*.
- Miles, N. (1988). Responses of pasture species to applied P on highly weathered soils. *Proceedings of Phosphorus Symposium*. Department of Agriculture and Water Supply, Pretoria. pp. 159-163.
- Miles, N. (1991). Nutrition of intensive pastures in the summer rainfall areas of southern Africa. *Journal of the Grassland Society of Southern Africa*, 8(2), 39-48.
- Miles, N., and Farina, M. P. W. (2014). Towards the more efficient use of fertiliser potassium: prediction of 'slowly-available' potassium reserves in soils. In: *Proceedings of the South African Sugar Technologists' Association*, Vol. 87, pp. 330-333.
- Milford, G. F. J., and Johnston, A. E. (2007). Potassium and nitrogen interactions in crop production. International Fertiliser Society.
- Miljkovic, N. S., Matthews, B. C., and Miller, M. H. (1966). The available boron content of the genetic horizons of some Ontario soils: I. The relationship between water-soluble boron and other soil properties. *Canadian Journal of Soil Science*, 46(2), 133-138.
- Millard, P., and C. M. Thomson. (1989). The effect of the autumn senescence of leaves on the internal cycling of nitrogen for the spring growth of apple trees. *Journal of Experimental Botany* 40, (11), 1285-1289.
- Miller, D. A., and Smith, R. K. (1977). Influence of boron on other chemical elements in alfalfa. *Communications in Soil Science and Plant Analysis*, 8(6), 465-478.
- Minhas, P.S., and Sharma, O.P. (2003). Management of soil salinity and alkalinity problems in India. *Journal of Crop Production* 7(1-2), 181-230.
- Ministry of Agriculture, Fisheries and Food (MAFF). (1988). Fertiliser recommendations for agricultural and horticultural crops. 5th edition. HMSO, London.
- Minnaar, H. R. (1984). A study of germination and flowering in *Cichorium intybus*. L. MSc thesis, Department of Plant Sciences. Rhodes University, Grahamstown, South Africa.

- Moll, R. H., Kamprath, E. J., and Jackson, W. A. (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilisation. *Agronomy Journal* 74(3), 562-564.
- Mon, R., Iurrtia, C., Botta, G. F., Pozzolo, O., Melcón, F. B., Rivero, D., and Bomben, M. (2007). Effects of supplementary irrigation on chemical and physical soil properties in the rolling Pampa region of Argentina. *Ciencia e Investigación Agraria*, 34(3), 187-194.
- Moody, P. W., and Bell, M. J. (2006). Availability of soil potassium and diagnostic soil tests. *Soil Research*, 44(3), 265-275.
- Moosavi, S. G. R. (2012). Effects of irrigation and nitrogen (N) fertilization levels on yield, morphological traits and water use efficiency of chicory (*Cichorium intybus* L.). *Journal of Medicinal Plants Research* 6(31), 4647-4652.
- Morrill, L. G., Hill, W. E., Chrudilmsky, W. W., Ashlock, L. O., Tripp, L. D., Tucker, B. B., and Weatherly, L. (1977). Boron requirements of Spanish peanuts in Oklahoma: Effects on yield and quality and interaction with other nutrients. *Oklahoma State University, Report Number: MNP-99*.
- Mortvedt, J. J., Giurdano, P. M., and W. L. Lindsay. (1972). Micronutrients in agriculture. *Soil Science Society of America*. Madison, WI. p666.
- Mortvedt, J. J., and Woodruff, J. R. (1993). Technology and application of boron fertilisers for crops. *Boron and its role in crop production*. CRC Press, Boca Raton, FL, 158-174.
- Moseley, G., and Baker, D. H. (1991). The efficacy of a high magnesium grass cultivar in controlling hypomagnesaemia in grazing animals. *Grass and Forage Science*, 46(4), 375-380.
- Mottram, D.S., Wedzicha, B.L., and Dodson, A.T. (2002). Food chemistry: acrylamide is formed in the Maillard reaction. *Nature* 419(6906), 488-449.
- Mukherjee, K. L. (1969). Microelement composition of sugarcane leaves during their growth and senescence. *Journal of Indian Botanical Science*, 47, 180-184.
- Mulvaney, R. L., Khan, S. A., and Mulvaney, C. S. (1997). Nitrogen fertilisers promote denitrification. *Biology Fertility of Soils*, 24(2), 211-220.
- Munson, R. D., and Nelson, W. L. (1963). Movement of applied potassium in soils. *Journal of Agricultural and Food Chemistry*, 11(3), 193-201.
- Murphy, J., and Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, 27, 31-36.
- Muttucumar, N., Halford, N. G., Elmore, J. S., Dodson, A. T., Parry, M., Shewry, P. R., and Mottram, D. S. (2006). Formation of high levels of acrylamide during the processing of flour derived from sulfate-deprived wheat. *Journal of Agricultural and Food Chemistry* 54(23), 8951-8955.

- Muttucumaru, N., Powers, S. J., Elmore, J. S., Mottram, D. S., and Halford, N. G. (2013). Effects of nitrogen and sulfur fertilization on free amino acids, sugars, and acrylamide-forming potential in potato. *Journal of Agricultural and Food Chemistry* 61(27), 6734-6742.
- Natural Resources Working Group, (2013). Bioresource Programme: A Natural Resources Classification System for KwaZulu-Natal. Version 9. KwaZulu-Natal, Department of Agriculture and Environmental Affairs, Internal Report, Pietermaritzburg.
- Neel, J.P.S., Alloush, G.A., Belesky, D.P., and Clapham, W.M. (2002). Influence of rhizosphere ionic strength on mineral composition, dry matter yield and nutritive value of forage chicory. *Journal of Agronomy and Crop Science* 188(6), 398-407.
- Nelson, W. L., Barber, S. A., and Sprague, H. B. (1964). Hunger signs in crops. *Hunger signs in crops*.
- Neuweiler, R., Krauss, J., Konrad, P., and Imhof, T. (2007). Optimised N-fertilization in the production of chicory. *Agrarforschung Schweiz* 14(11 and 12), 530-535.
- Nevens, F. and Reheul, D. (2002). The nitrogen- and non-nitrogen- contribution effect of ploughed grass leys on the following crops: determination and optimum use. *European Journal of Agronomy*, 16(1), 57-74.
- Niaz, A., Ibrahim, M., Ahmad, N., and Anwar, S. A. (2002). Boron contents of light and medium textured soils and cotton plants. *International Journal of Agriculture and Biology*, 4, 534-536.
- Niaz, A., Ranjha, A. M., Rahmatullah, A. H., and Waqas, M. (2007). Boron status of soils as affected by different soil characteristics—pH, CaCO₃, organic matter and clay contents. *Pakistan Journal of Agricultural Science*, 44(3), 428-435.
- Noppakoonwong, R. N., Bell, R. W., Dell, B., and Loneragan, J. F. (1993). An effect of shade on the boron requirement for leaf blade elongation in black gram (*Vigna mungo* L. Hepper). *Plant and Soil*, 155(1), 317-320.
- Nyborg, M., and Hoyt, P. B. (1970). Boron deficiency in turnip rape grown on Gray Wooded soils. *Canadian Journal of Soil Science*, 50(1), 87-8.
- Öborn, I., Andrist-Rangel, Y., Askegaard, M., Grant, C. A., Watson, C. A., and Edwards, A. C. (2005). Critical aspects of potassium management in agricultural systems. *Soil Use and Management*, 21(1), 102-112.
- Oertli, J. J., and Roth, J. A. (1969). Boron nutrition of sugar beet, cotton, and soybean. *Agronomy Journal*, 61(2), 191-195.
- Offiah, O., and Axley, J. H. (1988). Improvement of boron soil test. *Communications in Soil Science and Plant Analysis*, 19(13), 1527-1542.
- O'Geen, A., Pettygrove, S., Southard, R., Minoshima, H., and Verdegaal, P. (2008). Soil-landscape model helps predict potassium supply in vineyards. *California Agriculture*, 62(4), 195-201.

- Ohta, K., Hamada, S., and Nakamura, T. (1993). Production of high concentrations of ethanol from inulin by simultaneous saccharification and fermentation using *Aspergillus niger* and *Saccharomyces cerevisiae*. *Applied and Environmental Microbiology* 59(3), 729-733.
- Okazaki, E., and Chao, T. T. (1968). Boron adsorption and desorption by some Hawaiian soils. *Soil Science*, 105(4), 255-259.
- Orchard, E.R., and Van Rooyen, C. (1953). Chicory production in South Africa. Science Bulletin No. 339. Department of Agriculture, Union of South Africa.
- Pal, Y., Gilkes, R. J., and Wong, M. T. F. (1999). The forms of potassium and potassium adsorption in some virgin soils from south-western Australia. *Soil Research*, 37(4), 695-710.
- Papetti, D. Mascherpaa, C. Carazzonea et al., (2013). Identification of organic acids in *Chicorium intybus* inhibiting virulence related properties of oral pathogenic bacteria. *Food and Chemistry*, 138, (2), 1706-1712.
- Parfitt, G. D. (1976). Surface chemistry of oxides. *Pure and Applied Chemistry*, 48(4), 415-418.
- Parker, D. R., and Gardner, E. H. (1981). The determination of hot-water-soluble boron in some acid Oregon soils using a modified azomethine-H procedure. *Communications in Soil Science and Plant Analysis*, 12(12), 1311-1322.
- Parker, D. R., Hendricks, G. J. and Sparks, D. L. (1989a). Potassium in Atlantic Coastal Plain soils: II. Crop responses and changes in soil potassium under intensive management. *Soil Science Society of America Journal* 53(2): 397-401.
- Parker, D. R., Sparks, D. L., Hendricks, G. J. and Sadusky, M. C. (1989b). Potassium in Atlantic Coastal Plain soils: I. Soil characterization and distribution of potassium. *Soil Science Society of America Journal* 53(2): 392-396.
- Parr, A. J. and Loughman, B. C. (1983) Boron and membrane functions in plants. In: *Metals and Micronutrients: Uptake and Utilisation by Plants* (Annual Proceedings of the Phytochemical Society Europe No. 21); D.A. Robb and W.S. Pierpoint, (Eds), pp. 87-107. Academic Press, London.
- Patel, B. S., Barevidia, T. N., Patel, J. C., and Baldha, N. M. (1990). Response of chicory to different fertility levels. *Indian Journal of Agronomy* 35(3), 319-320.
- Patel, J. R., Patel, J. B., Upadhyay, P. N., and Usadadia, V. P. (2000). The effect of various agronomic practices on the yield of chicory (*Cichorium intybus*). *The Journal of Agricultural Science* 135(3), 271-278.
- Patel, N. K. (1967). Effect of various Ca-B and K-B ratios on the growth and chemical composition of aromatic strain of Bedi tobacco. *Indian Society of Soil Science*, 14, 241-251.
- Patel, R. R. (1958). *Studies on chicory*. M.Sc. (Agri.) thesis, Gujarat Agricultural University, Sardarkrushinagar, India.

- Pearce, R. (1947). Chicory in pasture mixtures. *Agriculture, London*, 53, 501-503.
- Peterson, J. R., and MacGregor, J. M. (1966). Boron fertilisation of corn in Minnesota. *Agronomy Journal*, 58(2), 141-142.
- Pettersson, S. (1984). Effects of nitrate on influx, efflux and translocation of potassium in young sunflower plants. *Physiologia Plantarum*, 61(4), 663-669.
- Pettygrove, S., O'Geen, T., and Southard, R. (2011). Potassium fixation and its significance for California crop production. *Better Crops with Plant Food*, 95(4), 16-18.
- Plank, C. O. (1989). Plant analysis handbook for Georgia. Cooperative Extension Service, University of Georgia College of Agriculture.
- Power, P. P., and Woods, W. G. (1997). The chemistry of boron and its speciation in plants. *Plant and Soil*, 193(1), 1-13.
- Prasad, R. (2009). Potassium fertilisation recommendations for crops need rethinking. *Indian Journal of Fertilisers*, 5(8), 31-33.
- Prinsloo, G. C. (1986). Black root rot of chicory in South Africa. *Phytophylactica*, 18(4), 225-226.
- Pujos, A., and Morard, P. (1997). Effects of potassium deficiency on tomato growth and mineral nutrition at the early production stage. *Plant and Soil*, 189(2), 189-196.
- Quémener, J. (1979). The measurement of soil potassium. IPI Research Topics No. 4. International Potash Institute CH-3048 Bern-Worblaufen, Switzerland.
- Rashid, A., and Ryan, J. (2004). Micronutrient constraints to crop production in soils with Mediterranean-type characteristics: a review. *Journal of Plant Nutrition*, 27(6), 959-975.
- Rausel-Colom, J. A. (1964). Small-angle X-ray diffraction study of the swelling of butylammonium-vermiculite. *Transactions of the Faraday Society*, 60, 190-201.
- Raven, J. A. (1980). Short-and long-distance transport of boric acid in plants. *New Phytologist*, 84(2), 231-249.
- Rayment, G. (2013). Total potassium to exchangeable potassium ratios as a guide to sustainable soil potassium supply. *Communications in Soil Science and Plant Analysis*, 44(1-4), 113-119.
- Razzaq, A., and Rafiq, M. (1996). Soil classification and survey. *Soil Science*, 405-437.
- Read, J. J., Reddy, K. R., and Jenkins, J. N. (2006). Yield and fiber quality of upland cotton as influenced by nitrogen and potassium nutrition. *European Journal of Agronomy*, 24(3), 282-290.

Red Tractor Farm Assurance (RTFA). (2010). Crop specific protocol for the United Kingdom: Chicory. [Online]. Available at: http://www.assuredproduce.co.uk/resources/000/528/617/chicory_2010_final.pdf. Accessed on 8/2/2016.

Red Tractor Farm Assurance (RTFA). (2015). Crop specific protocol for the United Kingdom: Chicory. [Online]. Available at: http://www.assuredproduce.co.uk/resources/000/528/617/chicory_2015_final.pdf. Accessed on 8/2/2016.

Reerink, J. (1992). *Onderzoek naar factoren en processen die de produktie en kwaliteit van witlof beïnvloeden: samenvatting en aanbevelingen* (No. 169). CABO-DLO.

Reisenauer, H. M., Walsh, L. M., and Hoef, R. G. (1973). Testing soils for sulphur, boron, molybdenum, and chlorine. *Soil Testing and Plant Analysis*, 173-200.

Reitemeier, R. F. (1951). Soil potassium. *Advances in Agronomy*, 3, 113-164.

Rengel, Z., and Damon, P. M. (2008). Crops and genotypes differ in efficiency of potassium uptake and use. *Physiologia Plantarum*, 133(4), 624-636.

Reuter, D., and Robinson, J. B. (Eds.). (1997). *Plant analysis: an interpretation manual*. CSIRO publishing.

Rich, C. I. (1968). Mineralogy of soil potassium. *The role of potassium in agriculture*, 79-108.

Richards, J. E., and Bates, T. E. (1988). Studies on the potassium-supplying capacities of southern Ontario soils. II. Nitric acid extraction of nonexchangeable K and its availability to crops. *Canadian Journal of Soil Science*, 68(2), 199-208.

Ritsema, T., and Smeekens, S. (2003). Fructans: beneficial for plants and humans. *Current Opinion in Plant Biology* 6(3), 223-230.

Roberfroid, M. B. (1999). Caloric value of inulin and oligofructose. *The Journal of Nutrition* 129(7), 1436S-1437S.

Roberts, R. K., Gersman, J. M., and Howard, D. D. (2000). Soil-and foliar-applied boron in cotton production: an economic analysis. *Journal of Cotton Science*, 4(3), 171-177.

Robinson, D. (1994). The responses of plants to non-uniform supplies of nutrients. *New Phytologist*, 127(4), 635-674.

Römheld, V. and Kirkby, E.A. (2010). Research on potassium in agriculture: Needs and prospects. *Plant and Soil* 335(1-2), 155-180.

Ruffy Jr, T. W., Raper Jr, C. D., and Huber, S. C. (1984). Alterations in internal partitioning of carbon in soybean plants in response to nitrogen stress. *Canadian Journal of Botany* 62(3), 501-508.

- Russell, E.W. (1973). Soil conditions and plant growth. 10th ed. Longman Ltd., London.
- Ruzzo, E.K., and 42 other authors. (2013). Deficiency of asparagine synthetase causes congenital microcephaly and a progressive form of encephalopathy. *Neuron* 80(2), 429-441.
- Ryan, J., Miyamoto, S., and Stroehlein, J. L. (1977). Relation of solute and sorbed boron to the boron hazard in irrigation water. *Plant and Soil*, 47(1), 253-256.
- Ryden, P., Sugimoto-Shirasu, K., Smith, A. C., Findlay, K., Reiter, W. D., and McCann, M. C. (2003). Tensile properties of Arabidopsis cell walls depend on both a xyloglucan cross-linked microfibrillar network and rhamnogalacturonan II-borate complexes. *Plant Physiology*, 132(2), 1033-1040.
- Saad, N., Delattre, C., Urdaci, M., Schmitter, J. M., and Bressollier, P. (2013). An overview of the latest advances in probiotic and prebiotic field. *LWT-Food Science and Technology* 50(1), 1-16.
- Sah, R. N., Geng, S., Puri, Y. P., and Rubatzky, V. E. (1987). Evaluation of four crops for nitrogen utilization and carbohydrate yield. *Nutrient Cycling in Agroecosystems*, 13(1), 55-70.
- Sakal, R., Sinha, R. B., and Singh, A. P. (1988). Effect of boron application on blackgram and chickpea production in calcareous soil. *Fertiliser News*, 33(2), 27-30.
- Saltali, K., Bilgili, A. V., Tarakcioglu, C., and Durak, A. (2005). Boron adsorption in soils with different characteristics. *Asian Journal of Chemistry*, 17(4), 2487.
- Sarrazyn, R., and Deckers, S. (1991). La composition des racines de Witloof, leur développement et la fertilization recommandée pendant le forçage. *Compte rendu de la XI biennale de l'endive, Arras*, B15-B70.
- Sayre, J.D. (1958). The accumulation of boron in margins of corn leaves. In: Trace elements. C.B. Lamb, (Ed). Pages 245-250 Academic Press, New York.
- Schittenhelm, S. (1999). Agronomic performance of root chicory, Jerusalem artichoke, and sugarbeet in stress and nonstress environments. *Crop Science* 39(6), 1815-1823.
- Schober, B. M., and Vermeulen, T. (1999). Enzymatic maceration of witloof chicory by the soft rot bacteria *Erwinia carotovora subspecies carotovora*: the effect of nitrogen and calcium treatments of the plant on pectic enzyme production and disease development. *European Journal of Plant Pathology*, 105(4), 341-349.
- Schon, M. K., and Blevins, D. G. (1990). Foliar boron applications increase the final number of branches and pods on branches of field-grown soybeans. *Plant Physiology*, 92(3), 602-607.
- Schreuder, R., van Leeuwen, M., Spruijt, J., van der Voort, M., van Asperen, P., and Hendriks-Goossens, V. (2009). Kwantitatieve informative, akkerbouw en vollegrondsgroenteteelt. Praktijkonderzoek Plant en Omgeving B.V., Lelystad.

- Schroeder, B. L., and Wood, A. W. (2002). A re-evaluation of the basis for deriving potassium fertiliser recommendations in the Australian sugar industry. In: *Proceedings-Australian Society of Sugarcane Technologists* (pp. 281-289). PK Editorial Services.
- Schroeder, B., Panitz, J., Wood, A., Moody, P. W., and Salter, B. (2007). *Soil-specific nutrient management guidelines for sugarcane production in the Bundaberg district*. BSES Limited.
- Schroeder, D. (1979). Structure and weathering of potassium containing minerals. *Proceedings Congress International Potash Institute*. 11, pp. 43–63.
- Schroth, G. and Sinclair, F.L. (Eds) (2003). *Trees, crops and soil fertility: Concepts and research methods*. CABI Publishing, Oxon, United Kingdom.
- Schubert, E., Mengel, K. and Schubert, S. (1990). Soil pH and calcium effect on nitrogen fixation and growth of broad bean. *Agronomy Journal*, 82(5), 969-972.
- Scott, A. D., and Smith, S. (1966). Susceptibility of interlayer potassium in micas to exchange with sodium. In: *Proceedings of the Clays and Clay Minerals: Proceedings of the Fourteenth National Conference, Berkeley, California* (p. 69).
- Seghatoleslami, M. J., Mousavi, G., and Javadi, H. (2014). Chicory (*Cichorium intybus*) responses to nitrogen and plant density in Birjand, Iran. *International Journal of Biosciences* 4(9), 56-61.
- Sharpley, A. N. (1990). Reaction of fertiliser potassium in soils of differing mineralogy. *Soil Science*, 149(1), 44-51.
- Shayan, A., and Davey, B. G. (1978). A universal dimensionless phosphate adsorption isotherm for soil. *Soil Science Society of America Journal*, 42(6), 878-882.
- Shiffler, A. K., Jolley, V. D., Christopherson, J. E., Webb, B. L., and Haby, V. A. (2005). Pressurized hot water and DTPA-sorbitol as viable alternatives for soil boron extraction. II. Correlation of soil extraction to responses of boron-fertilized alfalfa. *Communications in Soil Science and Plant Analysis*, 36(15-16), 2189-2207.
- Shorrocks, V.M. (1974). Boron deficiency – it's prevention and cure. Borax Consolidated Ltd., London, U.K.
- Shorrocks, V. (1997). The occurrence and correction of boron deficiency. *Plant and Soil* 193(1-2), 121-148.
- Sidhu, A. S., Narwal, R. P., and Brar, J. S. (2004). Adsorption-desorption behaviour of lead in soils amended with different organic materials. *Journal of the Indian Society of Soil Science*, 52(1), 43-49.
- Sillanpää, M. (1982). *Micronutrients and the nutrient status of soils: a global study* (No. 48). Food and Agriculture Organisation.
- Sillanpää, M. (1990). *Micronutrient assessment at the country level: an international study*. Food and Agriculture Organisation. Soils Bulletin 63, Rome, Italy.

- Silva, J. A., and Uchida, R. S. (2000). Plant nutrient management in Hawaii's soils: Approaches for tropical and subtropical agriculture. University of Hawaii.
- Silva, N. M. D., Carvalho, L. H., Kondo, J. I., Bataglia, O. C., and Abreu, C. A. D. (1995). Ten years of cotton fertilization with boron. *Bragantia*, 54(1), 177-185.
- Simmelsgaard, S. E. (1996). Plant nutrients in subsurface drainage water and soil water. *SP rapport*, 7.
- Sims, J.T. and Johnson, G.V. (1991). Micronutrient soil tests. In: *Micronutrients in agriculture* 2nd ed. (J.J. Mortvedt, F.R. Cox, L. M. Shuman and R.M. Welch, Eds.), pp. 427-476. SSSA Book Series No.4, Madison, WI.
- Singh, B. B., and Jones, J. P. (1975). Use of sorption-isotherms for evaluating potassium requirements of plants. *Soil Science Society of America Journal*, 39(5), 881-886.
- Sinha, H. (1961). Effect of potassium-boron interactions upon growth and composition of soybeans vegetable crops. Ph.D. dissertation, University of Missouri.
- Sinha, R.B., R. Sakal, A.P. Singh, and N.S. Bhogal. (1991). Response of some field crops to boron application in calcareous soils. *Journal Indian Society Soil Science*, 39(1), 118-122.
- Slaton, N. A., Golden, B. R., DeLong, R. E., and Mozaffari, M. (2010). Correlation and calibration of soil potassium availability with soybean yield and trifoliolate potassium. *Soil Science Society of America Journal*, 74(5), 1642-1651.
- Smith, C.A., and Wood, E.J. (1991). Basic principles; polysaccharides. In: *Molecular and Cell Biochemistry (biological molecules)*. (Eds. S. Firman and J. Ockenden), Chapman and Hall, New York, USA. pp. 165-166.
- Smith, G. S., Cornforth, I. S., and Henderson, H. V. (1985). Critical leaf concentrations for deficiencies of nitrogen, potassium, phosphorus, sulphur, and magnesium in perennial ryegrass. *New Phytologist*, 101(3), 393-409.
- Snäll, S., and Liljefors, T. (2000). Leachability of major elements from minerals in strong acids. *Journal of Geochemical Exploration*, 71(1), 1-12.
- Soil Classification Working Group, 1991. Soil Classification: A Taxonomic System for South Africa: A Report on a Research Project Conducted Under the Auspices of the Soil and Irrigation Research Institute. Department of Agricultural Development.
- Soil Survey Staff. (2014). Keys to soil taxonomy. (12th edition). *United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS)*.
- Soja, G., and Soja, A. M. (1995). Ozone effects on dry matter partitioning and chlorophyll fluorescence during plant development of wheat. *Water, Air, and Soil Pollution*, 85(3), 1461-1466.

- Solis, P., and Torrent, J. (1989). Phosphate sorption by calcareous Vertisols and Inceptisols of Spain. *Soil Science Society of America Journal*, 53(2), 456-459.
- Sowokinos, J. R., and Preston, D. A. (1988). Maintenance of potato processing quality by chemical maturity monitoring (CMM).
- Sparks, D. L. (1987). Potassium dynamics in soils. In *Advances in Soil Science* (pp. 1-63). Springer, New York, NY.
- Sparks, D. L. (2001). Elucidating the fundamental chemistry of soils: past and recent achievements and future frontiers. *Geoderma*, 100(3), 303-319.
- Sparks, D. L., and Huang, P. M. (1985). Physical chemistry of soil potassium. *Potassium in Agriculture*, 201-276.
- Sparks, D. L., and Liebhardt, W. C. (1981). Effect of long-term lime and potassium applications on quantity-intensity (Q/I) relationships in sandy soil. *Soil Science Society of America Journal*, 45(4), 786-790.
- Sparks, D. L., Martens, D. C. and Zelazny, L. W. (1980). Plant uptake and leaching of applied and indigenous potassium in Dothan soils. *Agronomy Journal* 72(3): 551-555.
- Sposito, G. (1980). Derivation of the Freundlich equation for ion exchange reactions in soils. *Soil Science Society of America Journal*, 44(3), 652-654.
- Springob, G., and Richter, J. (1998). Measuring interlayer potassium release rates from soil materials. II. A percolation procedure to study the influence of the variable 'solute K' in the < 1-10 μM range. *Journal of Plant Nutrition and Soil Science*, 161(3), 323-329.
- Stinson, C. H. (1953). Relation of water-soluble boron in Illinois soils to boron content of alfalfa. *Soil Science*, 75(1), 31-36.
- Street, R. A., Sidana, J., and Prinsloo, G. (2013). *Cichorium intybus*: Traditional uses, phytochemistry, pharmacology, and toxicology. *Evidence-Based Complementary and Alternative Medicine* 2013.
- Stromberger, J. A., Tsai, C. Y., and Huber, D. M. (1994). Interactions of potassium with nitrogen and their influence on growth and yield potential in maize. *Journal of Plant Nutrition*, 17(1), 19-37.
- Stumpe, J. M., and Vlek, P. L. (1991). Acidification induced by different nitrogen sources in columns of selected tropical soils. *Soil Science Society of America Journal*, 55(1), 145-151.
- Su, C., Evans, L. J., Bates, T. E., and Spiers, G. A. (1994). Extractable soil boron and alfalfa uptake: calcium carbonate effects on acid soil. *Soil Science Society of America Journal*, 58(5), 1445-1450.
- Sumner, M.E. and Farina, M.P.W. (1986). Phosphorus interactions with other nutrients and lime in field cropping systems. *Advances in Soil Science*, 5, 210-236.

- Sun, L., Long, X. H., Li, H. Y., and Liu, Z. P. (2009). Effects of different concentration sea water on Chicory seedlings growth and physiological characteristics. *Chinese Journal of Ecology*, 28, 405-410.
- Sutradhar, A. K., Kaiser, D. E., Rosen, C. J., and Lamb, J. A. (2016). Boron for Minnesota soils. *University of Minnesota Extension Publications AG FO-00723-C*.
- Syers, J.K. (2003) Potassium in soils: current concepts. In: Johnston AE (Ed.) Proceedings of the IPI Golden Jubilee Congress 1952–2002 held at Basel Switzerland 8–10 Oct 2002. Feed the soil to feed the people. The role of potash in sustainable agriculture. International Potash Institute, Basel, pp. 301–310.
- Takkar, P. N., Chhibba, I. M., and Mehta, S. K. (1989). Twenty years of coordinated research on micronutrients in soils and plants, 1967-87.
- Tanaka, H. (1967). Boron adsorption by plant roots. *Plant and Soil*, 27(2), 300-302.
- Tanji, K. K. (1970). A computer analysis on the leaching of boron from stratified soil columns. *Soil Science*, 110(1), 44-51.
- Tareke, E., Rydberg, P., Karlsson, P., Eriksson, S., and Törnqvist, M. (2002). Analysis of acrylamide, a carcinogen formed in heated foodstuffs. *Journal of Agricultural Food Chemistry* 50(17), 4998-5006.
- Temkin, M. I. (1940). Kinetics of heterogeneous catalysis. *Journal of Physical Chemistry (USSR)*, 14, 1153-1158.
- Terman, G. L. (1977). Yields and nutrient accumulation by determinate soybeans, as affected by applied nutrients. *Agronomy Journal*, 69(2), 234-238.
- Terry, N. (1970). Developmental Physiology of Sugar-Beet: II. Effects of temperature and nitrogen supply on the growth, soluble carbohydrate content and nitrogen content of leaves and roots. *Journal of Experimental Botany*, 21(2), 477-496.
- Thompson, L. M., Black, C. A., and Zoellner, J. A. (1954). Occurrence and mineralisation of organic phosphorus in soils, with particular reference to associations with nitrogen, carbon, and pH. *Soil Science*, 77(3), 185-196.
- Tisdale, S. L., Nelson, W. L., Beaton, J. D., and Havlin, J. L. (1993). Soil acidity and basicity. *Soil Fertility and Fertilizers, 5th^{ed}*. Macmillan, New York, pp. 364-404.
- Touchton, J. T., and Boswell, F. C. (1975). Effects of B application on soybean yield, chemical composition, and related characteristics. *Agronomy Journal*, 67(3), 417-420.
- Trehan, S. P., El Dessougi, H., and Claassen, N. (2005). Potassium efficiency of 10 potato cultivars as related to their capability to use nonexchangeable soil potassium by chemical mobilization. *Communications in Soil Science and Plant Analysis*, 36(13-14), 1809-1822.

Trehan, S. P., and Sharma, R. C. (2002). Potassium uptake efficiency of young plants of three potato cultivars as related to root and shoot parameters. *Communications in Soil Science and Plant Analysis*, 33(11-12), 1813-1823.

Truog, E. (1946). The liming of soils. Science in farming. USDA Yearbook, 1941-1947, 566-576.

Tůma, J., Skalicky, M., Tumova, L., Blahova, P., and Rosulkova, M. (2004). Potassium, magnesium and calcium content in individual parts of *Phaseolus vulgaris* L. plant as related to potassium and magnesium nutrition. *Plant Soil and Environment*, 50(1), 18-26.

Ujwalaranade-Malvi, U. R. (2011). Interaction of micronutrients with major nutrients with special reference to potassium. *Karnataka Journal of Agricultural Sciences*, 24(1).

United States Salinity Laboratory Staff (USSLS) (1954). Diagnosis and improvement of saline and alkali soils. Agricultural handbook No. 60. United States Department of Agriculture, Washington DC, 160.

Upjohn, B., and Michalk, D. (1999). Does chicory tolerate soil acidity? Orange Agricultural Institute, New South Wales Agriculture. <http://grasslandnsw.com.au/news/wp-content/uploads/2011/09/Upjohn-Michalk-1999.pdf>

US Borax, (2009). [Online] Available at: <http://minerals.usgs.gov/minerals/pubs/commodity/boron/myb1-2009-boron.pdf>

Van Arkel, J., Vergauwen, R., Sévenier, R., Hakkert, J. C., van Laere, A., Bouwmeester, H. J., ... and van der Meer, I. M. (2012). Sink filling, inulin metabolizing enzymes and carbohydrate status in field grown chicory (*Cichorium intybus* L.). *Journal of Plant Physiology*, 169(15), 1520-1529.

Van Breemen, N., Mulder, J., and Driscoll, C. T. (1983). Acidification and alkalization of soils. *Plant and Soil*, 75(3), 283-308.

Van den Ende, W., De Roover, J., and Van Laere, A. (1999). Effect of nitrogen concentration on fructan and fructan metabolizing enzymes in young chicory plants (*Cichorium intybus*). *Physiologia Plantarum* 105(1), 2-8.

Van Hee, L., and Bockstaele, L. (1983). The cultivation of chicory. *Revue de l agriculture* 36(3), 1015-1024.

Van Nerum, K. V. (1983). De moderne witloofteelt: de teelt van witloofwortelen en de trek van witloof in containers. In: Van Nerum, K.V. (Ed.), De modern witloofteelt. Vereniging 'Het nieuwe witloof' VZW, WTC Tower 1, Brussels, Belgium, pp 73-77.

Van Wyk, B. E., Oudtshoorn, B. V., and Gericke, N. (1997). *Medicinal Plants of South Africa*. Briza.

- Vandendriessche, H., Sarrazyn, R., Calus, A., Deckers, S., Geypens, M., Verschelden, C., ... and Coysman, A. (1993). Invloed van de bodemfertiliteit en de N-bemesting op de samenstelling van de witloofwortel en het forceerresultaat. *De witloofwortelproduktie, basis van de rendabiliteit. 12de tweejaarlijkse internationale witloofdagen, Leuven, Belgium*, 2-12.
- Velthof, G. L., and Oenema, O. (1995). Nitrous oxide fluxes from grassland in the Netherlands: II. Effects of soil type, nitrogen fertilizer application and grazing. *European Journal of Soil Science*, 46(4), 541-549.
- Verma, G. P. (1963). Release of non-exchangeable potassium from soils and micaceous minerals during short periods of cropping in the greenhouse. Retrospective Theses and Dissertations. 2976. <http://lib.dr.iastate.edu/rtd/2976>.
- Verster, E., and Van Rooyen, T. H. (1993). Influence of intensive irrigation and cultivation on selected soil properties: Arid southern Namibia. *South African Journal of Plant and Soil*, 10(2), 63-69.
- Vlamiš, J., and Ulrich, A. (1971). Boron nutrition in the growth and sugar content of sugarbeets. *American Society of Sugar Beet Technology Journal*. Food and Agricultural Organization.
- Von Uexküll, H. R., and Mutert, E. (1995). Global extent, development and economic impact of acid soils. *Plant and Soil* 171(1), 1-15.
- Von Wirén, N., Gazzarrini, S., Gojon, A., and Frommer, W. B. (2000). The molecular physiology of ammonium uptake and retrieval. *Current Opinion in Plant Biology*, 3(3), 254-261.
- VSN International (VSNi) (2015). *GenStat for Windows* 18th Edition. VSN International, Hemel Hempstead, UK. Web page: GenStat.co.uk
- Walker, T. S., Bais, H. P., Grotewold, E., and Vivanco, J. M. (2003). Root exudation and rhizosphere biology. *Plant Physiology*, 132(1), 44-51.
- Warrington, K. (1923). The effect of boric acid and borax on the broad bean and certain other plants. *Annals of Botany*, 37(148), 629-672.
- Warrington, K. (1933). The influence of length of day on the response of plants to boron. *Annals of Botany*, 3(187), 429-458.
- Wear, J. I., and Patterson, R. M. (1962). Effect of soil pH and texture on the availability of water-soluble boron in the soil. *Soil Science Society of America Journal*, 26(4), 344-346.
- Weil, R. R., and Brady, N. C. (2016). *The nature and properties of soils*. Pearson.
- Wentworth, S. A. (1969). Illite. *Clay Science*, 3(6), 140-155.
- Wentworth, S. A., and Rossi, N. (1972). Release of potassium from layer silicates by plant growth and by NATPB extraction. *Soil Science*, 113(6), 410-416.

- Westermann, D. T., Tindall, T. A., James, D. W., and Hurst, R. L. (1994). Nitrogen and potassium fertilisation of potatoes: yield and specific gravity. *American Potato Journal*, 71(7), 417-431.
- White, P. J., and Broadley, M. R. (2003). Calcium in plants. *Annals of Botany*, 92(4), 487-511.
- Wild, A., and Mazaheri, A. (1979). Prediction of the leaching rate of boric acid under field conditions. *Geoderma*, 22(2), 127-136.
- Wilkinson, S.R., Grunes, D.L., and Sumner, M.E. (1999). Nutrient interactions in soil and plant nutrition. In: Handbook of soil science; Sumner, M.E., (Ed.), CRC Press: Boca Raton, FL.
- Wilson, R. G., Smith, J. A., and Yonts, C. D. (2004). Chicory root yield and carbohydrate composition is influenced by cultivar selection, planting, and harvest date. *Crop Science* 44(3), 748-752.
- Withers, P. J., Clay, S. D., and Breeze, V. G. (2001a). Phosphorus transfer in runoff following application of fertiliser, manure, and sewage sludge. *Journal of Environmental Quality*, 30(1), 180-188.
- Withers, P. J., Edwards, A. C., and Foy, R. H. (2001b). Phosphorus cycling in UK agriculture and implications for phosphorus loss from soil. *Soil Use and Management*, 17(3), 139-149.
- Withers, P. J., Nash, D. M., and Laboski, C. A. (2005). Environmental management of phosphorus fertilizers. *Phosphorus: Agriculture and the Environment*, 781-827.
- Withers, P. J., Sylvester-Bradley, R., Jones, D. L., Healey, J. R., and Talboys, P. J. (2014). Feed the crop not the soil: rethinking phosphorus management in the food chain. *Environmental Science and Technology*, 48(12), 6523-6530.
- Witter, E., and Johansson, G. (2001). Potassium uptake from the subsoil by green manure crops. *Biological Agriculture and Horticulture* 19(2), 127-141.
- Wolf, B. (1940). Factors influencing availability of boron in soil and its distribution in plants. *Soil Science*, 50(3), 209-218.
- Wood, A. W., Schroeder, B. L., and Stewart, R. L. (2003). The development of site-specific nutrient management guidelines for sustainable sugarcane production. In: *Proceedings-Australian Society of Sugar Cane Technologists* Vol. 25. PK Editorial Services.
- Wood, L. K., and DeTurk, E. E. (1941). The absorption of potassium in soils in non-replaceable forms. *Soil Science Society of America Journal*, 5(C), 152-161.
- Wood, R. A., and Meyer, J. H. (1986). Factors affecting potassium nutrition of sugarcane in South Africa. In: *Proceedings of the South African Sugar Technologists Association*, Vol.60, pp. 198-204.

- Woodruff, J. R. (1979). Soil boron and soybean leaf boron in relation to soybean yield 1. *Communications in Soil Science and Plant Analysis*, 10(6), 941-952.
- Woodruff, J.R., and Parks, C.L. (1980). Topsoil and subsoil potassium calibration with leaf K for fertility rating. *Agronomy Journal* 72: 392-396.
- Woyts, O.F. (1928). Culture of chicory in Belgium (Witloof). *Journal Ministry of Agriculture*, 5, 430-439.
- Yan, X., Wu, P., Ling, H., Xu, G, F. and Zhang, Q. (2006). Plant nutriomics in China: an overview. *Annals of Botany*, 98(3), 473-482.
- Youssef, R. A., and Chino, M. (1989). Root-induced changes in the rhizosphere of plants. I. pH changes in relation to the bulk soil. *Soil Science and Plant Nutrition*, 35(3), 461-468.
- Zhang, F., Cui, Z., Fan, M., Zhang, W., Chen, X., and Jiang, R. (2011). Integrated soil–crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. *Journal of Environmental Quality*, 40(4), 1051-1057.
- Zhang, F., Niu, J., Zhang, W., Chen, X., Li, C., Yuan, L., and Xie, J. (2010). Potassium nutrition of crops under varied regimes of nitrogen supply. *Plant and Soil*, 335(1-2), 21-34.
- Zobel, R. W., Alloush, G. A., and Belesky, D. P. (2006). Differential root morphology response to no versus high phosphorus, in three hydroponically grown forage chicory cultivars. *Environmental Experimental Botany*, 57(1), 201-208.
- Zörb, C., Senbayram, M., and Peiter, E. (2014). Potassium in agriculture—status and perspectives. *Journal of Plant Physiology*, 171(9), 656-669.

APPENDICES

Appendix 3.1: Long-term (1968-2012) mean climate at the Dundee Agricultural Research Station (Natural Resources Working Group, 2013)

	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)													
Median	651	126	98	79	30	8	2	2	8	24	62	96	116
Mean	743	134	106	80	42	18	10	12	17	35	70	99	120
Mean daily temperature (°C)													
Mean	17.1	21.3	21.4	20.0	17.3	14.0	11.1	11.2	13.5	16.7	18.3	19.6	20.8
Minimum	9.7	15.0	15.1	13.6	10.2	5.9	2.1	2.2	4.8	8.6	11.1	12.9	14.3
Maximum	24.5	27.6	27.7	26.6	24.4	22.1	20.0	20.2	22.2	24.8	25.4	26.4	27.2
Relative humidity (%)													
Mean monthly	65	72	72	72	68	65	57	59	58	58	64	67	70
Heat units													
Base 13		257	235	217	129	31	0	0	16	111	164	198	242
Base 12		288	263	248	159	62	0	0	47	141	195	228	273
Base 10		350	319	310	219	124	33	37	109	201	257	288	335
Base 5		505	459	465	369	279	183	192	264	351	412	438	490
Base 4.4		524	476	484	387	298	201	211	282	369	431	456	508
Evaporation (mm)													
A pan	1824	198	167	158	127	108	94	105	140	164	177	181	205
Sunshine													
MMSR* (MJ m ⁻² day ⁻¹)		23.9	22.4	20.7	17.8	15.0	13.7	14.3	16.0	18.6	20.1	22.1	27.4
Hour day ⁻¹ (Oct-Mar)	6.8												
Frost severity	Severe. On average 16 days of frost may occur during the year within a period of 68 days. Such frosts are expected during 87% of the years.												

* Mean monthly solar radiation

Appendix 3.2: Soil description of the Avalon soil form according to the Soil Classification Working Group (1991) terminology as found on the trial sites

Horizon	Depth (mm)	Description	Diagnostic horizons
A1	0-300	Moist; brown to dark brown (10YR 4/3); few fine faint brown mottles (10YR5/4); fine sandy loam; massive; loose; clear smooth transition	Orthic A
B11	300-600	Moist; yellowish brown (10YR5/6); common medium distinct red mottles (2.5YR4/4); common medium distinct brown mottles; sandy clay loam; massive; friable; clear smooth transition	Yellow-brown apedal B
B12	600-750	Moist; yellowish brown (10YR 5/6); common medium distinct red mottles (2.5YR5/4); sandy clay; massive; friable; gradual smooth transition	Yellow-brown apedal B
B2	750-900	Moist; light brownish grey (10YR 6/2); many coarse prominent grey mottles (10YR3/2); sandy clay; weak medium subangular blocky; slightly firm; abrupt transition	Soft plinthic B
C	>900	Sandstone of the Ecca Group , Vryheid Formation	

Appendix 3.3: Irrigation water quality

EC ¹ (mS m ⁻¹)	pH	Cations				Anions		SAR ²	TDS ³	Class of water ⁴
		(me L ⁻¹)				(me L ⁻¹)				
		Na	Ca	Mg	K	Total alkalinity	Cl			
45.68	7.01	2.92	1.09	1.28	0.52	3.5	2.5	2.68	278.65	C2-S1

¹Electrical conductivity; ²Sodium Adsorption Ratio, ³Total Dissolved Solutes, ⁴United States Salinity Laboratory Staff (USSLS) (1954)

Appendix 3.4: Soil analysis methodology

pH was measured using a gel filled combination glass electrode (Thermo scientific, Orion Star A211®) in a 1:2.5 soil:solution ratio in 1M KCl after stirring at 400 r.p.m. for 5 minutes and then standing for 30 minutes.

Exchangeable Ca and Mg were extracted in 1M KCl from a 1:10 soil:solution ratio after stirring at 400 r.p.m. for 10 minutes. An aliquot of the filtered extract was diluted with SrCl₂ and Ca and Mg determined by atomic absorption spectrophotometry (AAS) (Varian, Spectra AA 220FS®).

Extractable acidity was determined in a separate aliquot of the filtrate (diluted 1:1 with deionized water) by titration with 0.005M NaOH after the addition of 2-4 drops of phenolphthalein.

Phosphorus, K, Zn and Mn were extracted in a 1:10 soil:solution ratio using the Ambic-2 extractant (0.25 M NH₄CO₃ + 0.01 M Na₂EDTA + 0.01 M NH₄F + 0.05 g L⁻¹ Superfloc (N100), adjusted to pH 8 with a concentrated ammonia solution) after stirring at 400 r.p.m. for 10 minutes. Phosphorus was measured in an aliquot of the filtrate using a modification (Hunter, 1974) of the Murphy and Riley (1962) procedure. Potassium, Zn and Mn were measured by AAS.

Effective cation exchange capacity (ECEC) was calculated as the sum of KCl-extractable Ca, Mg, and acidity and Ambic-2 extractable K. Percent acid saturation of the ECEC was calculated as: extractable acidity x 100 / (Ca + Mg + K + extractable acidity).

Organic carbon and total N were estimated on the air dry soil samples by mid-infrared reflectance.

Organic carbon was determined by the Walkley-Black procedure (Allison et al., 1965). The organic matter was oxidized by potassium dichromate in a sulphuric acid medium. The excess dichromate was determined by titration with standard ferrous sulphate solution.

Particle size distribution was determined using the pipette method (Gee and Bauder, 1986) after removal of organic matter with hydrogen peroxide and dispersion with NaOH and sodium hexametaphosphate. Clay (<0.002 mm) and fine silt (0.002-0.02 mm) were determined by sedimentation and the sand fractions (very fine sand (0.05-0.10 mm), fine sand (0.10 - 0.25 mm), medium sand (0.25-0.50 mm) and coarse sand (0.50-2.0 mm)) by sieving (Day, 1965). Coarse silt (0.02-0.05 mm) was estimated by difference. The textural class of the soil was then determined from the textural triangle (Soil Classification Working Group, 1991).

Appendix 3.5: Leaf and root analysis methodology

Plant material was dried at 75°C, and milled to pass through a 0.84 mm sieve. Subsamples were then dry-ashed at 450°C overnight and taken up in 1M HCl. The P concentration was determined colorimetrically by the same method used for soil samples, and K, Na, Ca, Mg, Cu, Mn, and Zn were determined by AAS (Varian, Vista-MPX®). Samples for B analysis

were ashed separately, and B determined photometrically by the azomethine-H method (Gaines and Mitchell, 1979).

Total C, N and S were analyzed by the Automated Dumas dry combustion method using a LECO CNS 2000® (Leco Corporation, Michigan, USA; Matejovic, 1996).

Appendix 3.6: Chapter 3 (N x P x L trial) yield statistical analysis

Variate: Tons_ha_2012,Tons_ha_2013,Tons_ha_2014

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
rep stratum	1		174.43	174.43	0.37	
rep.block stratum	6		2795.75	465.96	7.02	
rep.block.Subject stratum						
N_level	3		4108.06	1369.35	20.63	<.001
P_level	3		595.99	198.66	2.99	0.035
L_level	3		3500.19	1166.73	17.58	<.001
N_level.P_level	9		1190.48	132.28	1.99	0.050
N_level.L_level	9		780.41	86.71	1.31	0.246
P_level.L_level	9		436.48	48.50	0.73	0.680
Residual	84		5574.81	66.37	2.83	
rep.block.Subject.Time stratum						
d.f. correction factor 0.7084						
Time	2		14213.15	7106.58	302.66	<.001
Time.N_level	6		2038.34	339.72	14.47	<.001
Time.P_level	6		548.38	91.40	3.89	0.004
Time.L_level	6		701.07	116.85	4.98	<.001
Time.N_level.P_level	18		319.53	17.75	0.76	0.702
Time.N_level.L_level	18		321.56	17.86	0.76	0.697
Time.P_level.L_level	18		193.96	10.78	0.46	0.941
Residual	180	(2)	4226.47	23.48		
Total	381	(2)	41582.71			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 block 3 Subject 10	10.94	s.e. 3.81
rep 1 block 1 Subject 1 Time Tons_ha_2012	-9.26	s.e. 3.32
rep 2 block 4 Subject 4 Time Tons_ha_2012	10.64	s.e. 3.32

Tables of means

Variate: Tons_ha_2012,Tons_ha_2013,Tons_ha_2014

Grand mean 36.73

Time	Tons_ha_2012	Tons_ha_2013	Tons_ha_2014		
	28.13	40.82	41.25		
N_level	0	1	2	3	
	31.76	35.90	39.12	40.15	
P_level	0	1	2	3	
	34.79	36.68	37.29	38.18	
L_level	0	1	2	3	
	32.08	36.71	37.67	40.47	
Time	N_level	0	1	2	3
Tons_ha_2012		27.64	28.43	29.17	27.30
Tons_ha_2013		33.06	40.09	43.58	46.54
Tons_ha_2014		34.59	39.18	44.61	46.62
Time	P_level	0	1	2	3
Tons_ha_2012		27.42	28.82	29.38	26.91
Tons_ha_2013		38.69	40.71	41.24	42.63
Tons_ha_2014		38.24	40.49	41.26	45.01
N_level	P_level	0	1	2	3
0		31.62	32.00	30.24	33.19
1		34.38	38.04	37.54	33.64
2		35.90	36.20	41.44	42.92
3		37.24	40.46	39.94	42.97
Time	L_level	0	1	2	3
Tons_ha_2012		25.89	26.48	29.39	30.78
Tons_ha_2013		35.33	42.74	41.60	43.59
Tons_ha_2014		35.03	40.91	42.03	47.03
N_level	L_level	0	1	2	3
0		26.60	33.28	32.19	34.97
1		29.73	35.43	40.45	38.00
2		35.19	38.67	39.11	43.50
3		36.81	39.47	38.93	45.41
P_level	L_level	0	1	2	3
0		29.90	35.64	35.62	37.98
1		31.97	37.87	37.33	39.53
2		33.96	37.25	36.66	41.29
3		32.50	36.09	41.07	43.07
Time	N_level	P_level	0	1	2
Tons_ha_2012	0		28.50	28.79	27.40
	1		27.62	29.17	30.94
	2		27.42	28.69	32.52
	3		26.15	28.65	26.67

Tons_ha_2013	0		33.54	33.46	30.43
	1		37.63	42.90	42.58
	2		40.36	39.89	45.21
	3		43.22	46.60	46.72
Tons_ha_2014	0		32.81	33.76	32.89
	1		37.90	42.04	39.10
	2		39.93	40.03	46.60
	3		42.34	46.14	46.44
Time	N_level	P_level	3		
Tons_ha_2012	0		25.89		
	1		25.98		
	2		28.04		
	3		27.73		
Tons_ha_2013	0		34.79		
	1		37.27		
	2		48.85		
	3		49.61		
Tons_ha_2014	0		38.90		
	1		37.68		
	2		51.87		
	3		51.58		
Time	N_level	L_level	0	1	2
Tons_ha_2012	0		25.75	27.45	28.27
	1		23.79	27.48	30.67
	2		28.29	26.04	31.00
	3		25.71	24.96	27.60
Tons_ha_2013	0		26.32	36.92	33.42
	1		33.98	41.52	45.07
	2		38.61	45.58	42.55
	3		42.42	46.95	45.35
Tons_ha_2014	0		27.74	35.48	34.90
	1		31.42	37.28	45.60
	2		38.67	44.39	43.79
	3		42.29	46.51	43.83
Time	N_level	L_level	3		
Tons_ha_2012	0		29.10		
	1		31.77		
	2		31.33		
	3		30.92		
Tons_ha_2013	0		35.56		
	1		39.81		
	2		47.57		
	3		51.44		
Tons_ha_2014	0		40.24		
	1		42.42		
	2		51.59		
	3		53.86		
Time	P_level	L_level	0	1	2
Tons_ha_2012	0		23.79	25.94	29.23
	1		27.73	28.52	28.44
	2		27.06	28.69	29.23
	3		24.96	22.78	30.65
Tons_ha_2013	0		33.80	41.30	39.15
	1		34.41	43.85	42.03
	2		37.25	43.04	40.19
	3		35.87	42.78	45.02

Tons_ha_2014	0	32.11	39.67	38.49
	1	33.77	41.25	41.53
	2	37.56	40.03	40.57
	3	36.67	42.71	47.53
Time	P_level	L_level		3
Tons_ha_2012	0			30.73
	1			30.60
	2			32.54
	3			29.25
Tons_ha_2013	0			40.51
	1			42.56
	2			44.46
	3			46.84
Tons_ha_2014	0			42.71
	1			45.42
	2			46.86
	3			53.12

Least significant differences of means (5% level)

Table	Time	N_level	P_level	L_level
rep.	128	96	96	96
d.f.	127.51	84	84	84
l.s.d.	1.271	2.338	2.338	2.338

Table	Time	Time	N_level	Time
	N_level	P_level	P_level	L_level
rep.	32	32	24	32
l.s.d.	3.217	3.217	4.677	3.217
d.f.	184.18	184.18	84	184.18

Except when comparing means with the same level(s) of

N_level	2.543			
d.f.	127.51			
P_level		2.543		
d.f.		127.51		
L_level				2.543
d.f.				127.51

Table	N_level	P_level	Time	Time
	L_level	L_level	N_level	N_level
			P_level	L_level
rep.	24	24	8	8
l.s.d.	4.677	4.677	6.434	6.434
d.f.	84	84	184.18	184.18

Except when comparing means with the same level(s) of

N_level.P_level		5.086		
d.f.		127.51		
N_level.L_level				5.086
d.f.				127.51

Table	Time			
	P_level			
	L_level			
rep.	8			
l.s.d.	6.434			
d.f.	184.18			
Except when comparing means with the same level(s) of				
P_level.L_level	5.086			

d.f. 127.51

(Not adjusted for missing values)

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Tons_ha_2012,Tons_ha_2013,Tons_ha_2014

Stratum	d.f.	s.e.	cv%
rep	1	0.953	2.6
rep.block	6	3.116	8.5
rep.block.Subject	84	4.703	12.8
rep.block.Subject.Time	180	4.846	13.2

Appendix 3.7: Chapter 3 (N x P x L trial) soil statistical analysis

Analysis of variance

Variate: %2010_ASAT_%,%2011_ASAT_%,%2012_ASAT_%,%2013_ASAT_%,%2014_ASAT_%

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	598.69	598.69	4.30	
rep.block stratum	6	835.33	139.22	3.87	
rep.block.Subject stratum					
N_kg_ha	3	264.23	88.08	2.45	0.069
P_kg_ha	3	71.37	23.79	0.66	0.578
L_t_ha	3	2643.65	881.22	24.50	<.001
N_kg_ha.P_kg_ha	9	513.51	57.06	1.59	0.133
N_kg_ha.L_t_ha	9	138.68	15.41	0.43	0.916
P_kg_ha.L_t_ha	9	209.79	23.31	0.65	0.753
Residual	84	3021.43	35.97	1.18	
rep.block.Subject.Time stratum					
d.f. correction factor 0.5719					
Time	4	159174.76	39793.69	1303.70	<.001
Time.N_kg_ha	12	437.54	36.46	1.19	0.308
Time.P_kg_ha	12	100.41	8.37	0.27	0.962
Time.L_t_ha	12	3906.37	325.53	10.66	<.001
Time.N_kg_ha.P_kg_ha	36	876.24	24.34	0.80	0.719
Time.N_kg_ha.L_t_ha	36	1109.08	30.81	1.01	0.453
Time.P_kg_ha.L_t_ha	36	498.97	13.86	0.45	0.981
Residual	364	11110.63	30.52		
Total	639	185510.69			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 block 1	-2.43	s.e. 1.14
rep 1 block 1 Subject 13	-6.10	s.e. 2.17
rep 1 block 1 Subject 1 Time %2010_ASAT_%	-12.93	s.e. 4.17
rep 1 block 1 Subject 2 Time %2010_ASAT_%	-15.66	s.e. 4.17
rep 1 block 1 Subject 3 Time %2010_ASAT_%	-14.65	s.e. 4.17
rep 1 block 1 Subject 4 Time %2010_ASAT_%	-24.76	s.e. 4.17
rep 1 block 1 Subject 9 Time %2010_ASAT_%	-16.85	s.e. 4.17
rep 1 block 1 Subject 14 Time %2010_ASAT_%	-13.59	s.e. 4.17
rep 1 block 2 Subject 8 Time %2010_ASAT_%	-12.58	s.e. 4.17
rep 1 block 3 Subject 8 Time %2010_ASAT_%	-14.39	s.e. 4.17
rep 2 block 2 Subject 14 Time %2010_ASAT_%	13.38	s.e. 4.17
rep 2 block 2 Subject 14 Time %2011_ASAT_%	-12.67	s.e. 4.17
rep 2 block 2 Subject 15 Time %2010_ASAT_%	15.82	s.e. 4.17
rep 2 block 3 Subject 2 Time %2010_ASAT_%	12.74	s.e. 4.17
rep 2 block 3 Subject 3 Time %2010_ASAT_%	13.76	s.e. 4.17

Tables of means

Variate: %2010_ASAT_%,%2011_ASAT_%,%2012_ASAT_%,%2013_ASAT_%,%2014_ASAT_%

Grand mean 12.55

Time	%2010_ASAT_%	%2011_ASAT_%	%2012_ASAT_%	%2013_ASAT_%	%2014_ASAT_%
	43.05	12.62	3.16	2.45	1.45
N_kg_ha	0	80	160	240	
	13.04	11.77	12.07	13.31	
P_kg_ha	0	40	80	120	
	12.27	12.25	12.59	13.07	
L_t_ha	0	2	4	8	
	15.47	13.38	11.02	10.32	
Time	N_kg_ha	0	80	160	240
%2010_ASAT_%		45.47	42.22	41.12	43.37
%2011_ASAT_%		14.16	10.88	11.94	13.53
%2012_ASAT_%		2.56	2.28	3.00	4.78
%2013_ASAT_%		1.84	2.28	2.75	2.91

%2014_ASAT_%		1.16	1.19	1.53	1.94
Time	P_kg_ha	0	40	80	120
%2010_ASAT_%		42.72	42.09	43.03	44.34
%2011_ASAT_%		11.66	12.66	12.81	13.38
%2012_ASAT_%		3.44	2.66	2.87	3.66
%2013_ASAT_%		2.37	2.06	2.78	2.56
%2014_ASAT_%		1.16	1.78	1.44	1.44

N_kg_ha	P_kg_ha	0	40	80	120
0		11.57	13.02	14.50	13.05
80		13.35	11.25	10.43	12.05
160		12.30	12.02	11.30	12.65
240		11.85	12.70	14.12	14.55

Time	L_t_ha	0	2	4	8
%2010_ASAT_%		43.28	42.16	43.16	43.59
%2011_ASAT_%		21.22	16.75	7.97	4.56
%2012_ASAT_%		6.75	3.53	1.31	1.03
%2013_ASAT_%		3.78	3.00	1.62	1.37
%2014_ASAT_%		2.31	1.44	1.03	1.03

N_kg_ha	L_t_ha	0	2	4	8
0		16.32	13.37	11.97	10.47
80		14.22	13.07	9.42	10.35
160		14.97	13.22	10.22	9.85
240		16.35	13.82	12.45	10.60

P_kg_ha	L_t_ha	0	2	4	8
0		15.02	13.27	10.80	9.97
40		15.52	12.45	11.20	9.82
80		14.40	13.35	11.28	11.33
120		16.92	14.42	10.80	10.15

Time	N_kg_ha	P_kg_ha	0	40	80
%2010_ASAT_%	0		41.88	47.38	45.62
	80		42.75	40.62	41.37
	160		44.12	37.25	40.38
	240		42.12	43.12	44.75
%2011_ASAT_%	0		11.25	13.25	18.88
	80		14.38	11.25	7.25
	160		11.00	14.25	9.88
	240		10.00	11.88	15.25
%2012_ASAT_%	0		1.88	1.62	4.38
	80		5.12	1.50	0.75
	160		2.50	4.00	2.50
	240		4.25	3.50	3.88
%2013_ASAT_%	0		1.62	1.62	2.50
	80		3.12	2.00	1.75
	160		2.87	2.87	2.12
	240		1.87	1.75	4.75
%2014_ASAT_%	0		1.25	1.25	1.12
	80		1.38	0.87	1.00
	160		1.00	1.75	1.62
	240		1.00	3.25	2.00

Time	N_kg_ha	P_kg_ha	120
%2010_ASAT_%	0		47.00
	80		44.12
	160		42.75

	240	43.50
%2011_ASAT_%	0	13.25
	80	10.62
	160	12.62
	240	17.00
%2012_ASAT_%	0	2.37
	80	1.75
	160	3.00
	240	7.50
%2013_ASAT_%	0	1.62
	80	2.25
	160	3.12
	240	3.25
%2014_ASAT_%	0	1.00
	80	1.50
	160	1.75
	240	1.50

Time	N_kg_ha	L_t_ha	0	2	4	8
%2010_ASAT_%	0		43.25	45.50	46.62	46.50
	80		45.50	42.00	38.62	42.75
	160		43.00	39.38	40.75	41.38
	240		41.38	41.75	46.62	43.75
%2011_ASAT_%	0		27.37	16.75	9.75	2.75
	80		18.25	15.37	4.37	5.50
	160		20.00	16.88	6.87	4.00
	240		19.25	18.00	10.88	6.00
%2012_ASAT_%	0		6.62	1.50	1.12	1.00
	80		2.62	3.87	1.62	1.00
	160		5.62	4.25	1.00	1.12
	240		12.12	4.50	1.50	1.00
%2013_ASAT_%	0		2.87	1.87	1.37	1.25
	80		3.12	3.00	1.50	1.50
	160		4.37	3.62	1.50	1.50
	240		4.75	3.50	2.12	1.25
%2014_ASAT_%	0		1.50	1.25	1.00	0.87
	80		1.62	1.12	1.00	1.00
	160		1.87	2.00	1.00	1.25
	240		4.25	1.37	1.12	1.00

Time	P_kg_ha	L_t_ha	0	2	4	8
%2010_ASAT_%	0		43.75	41.88	42.25	43.00
	40		41.50	41.50	44.38	41.00
	80		39.63	41.63	43.00	47.88
	120		48.25	43.63	43.00	42.50
%2011_ASAT_%	0		19.37	16.25	7.25	3.75
	40		22.75	15.12	7.75	5.00
	80		20.00	16.62	9.62	5.00
	120		22.75	19.00	7.25	4.50
%2012_ASAT_%	0		6.37	4.25	2.00	1.12
	40		6.25	2.25	1.12	1.00
	80		6.12	3.12	1.25	1.00
	120		8.25	4.50	0.87	1.00
%2013_ASAT_%	0		4.12	2.87	1.37	1.12
	40		3.25	2.25	1.62	1.12
	80		4.62	3.25	1.62	1.62
	120		3.12	3.62	1.87	1.62
%2014_ASAT_%	0		1.50	1.12	1.12	0.87
	40		3.87	1.12	1.12	1.00
	80		1.62	2.12	0.87	1.12

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	160	160	160
d.f.	208.16	84	84	84
l.s.d.	1.496	1.333	1.333	1.333

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	40	32
l.s.d.	3.040	3.040	2.667	3.040
d.f.	287.12	287.12	84	287.12

Except when comparing means with the same level(s) of

N_kg_ha	2.991			
d.f.	208.16			
P_kg_ha		2.991		
d.f.		208.16		
L_t_ha				2.991
d.f.				208.16

Table	N_kg_ha	P_kg_ha	Time	Time
	L_t_ha	L_t_ha	N_kg_ha	N_kg_ha
			P_kg_ha	L_t_ha
rep.	40	40	8	8
l.s.d.	2.667	2.667	6.080	6.080
d.f.	84	84	287.12	287.12

Except when comparing means with the same level(s) of

N_kg_ha.P_kg_ha			5.983	
d.f.			208.16	
N_kg_ha.L_t_ha				5.983
d.f.				208.16

Table	Time
	P_kg_ha
	L_t_ha
rep.	8
l.s.d.	6.080
d.f.	287.12

Except when comparing means with the same level(s) of

P_kg_ha.L_t_ha	5.983
d.f.	208.16

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %2010_ASAT_%,%2011_ASAT_%,%2012_ASAT_%,%2013_ASAT_%,%2014_ASAT_%

Stratum	d.f.	s.e.	cv%
rep	1	1.368	10.9
rep.block	6	1.319	10.5
rep.block.Subject	84	2.682	21.4
rep.block.Subject.Time	364	5.525	44.0

Analysis of variance

Variate: %2010_P_mg_L,%2011_P_mg_L,%2012_P_mg_L,%2013_P_mg_L,%2014_P_mg_L

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	4131.1	4131.1	5.36	
rep.block stratum	6	4620.6	770.1	2.88	
rep.block.Subject stratum					
N_kg_ha	3	529.1	176.4	0.66	0.579
P_kg_ha	3	49359.2	16453.1	61.51	<.001
L_t_ha	3	983.2	327.7	1.23	0.306
N_kg_ha.P_kg_ha	9	2866.8	318.5	1.19	0.312
N_kg_ha.L_t_ha	9	4575.2	508.4	1.90	0.063
P_kg_ha.L_t_ha	9	3401.8	378.0	1.41	0.196
Residual	84	22470.3	267.5	2.59	
rep.block.Subject.Time stratum					
d.f. correction factor 0.6266					
Time	4	50338.5	12584.6	121.72	<.001
Time.N_kg_ha	12	2013.1	167.8	1.62	0.124
Time.P_kg_ha	12	48768.4	4064.0	39.31	<.001
Time.L_t_ha	12	625.8	52.1	0.50	0.842
Time.N_kg_ha.P_kg_ha	36	2413.4	67.0	0.65	0.888
Time.N_kg_ha.L_t_ha	36	4837.1	134.4	1.30	0.170
Time.P_kg_ha.L_t_ha	36	2032.9	56.5	0.55	0.955
Residual	364	37633.2	103.4		
Total	639	241599.8			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 block 1	5.67	s.e. 2.69
rep 1 block 1 Subject 4	16.04	s.e. 5.93
rep 1 block 4 Subject 11	15.86	s.e. 5.93
rep 1 block 1 Subject 4 Time %2010_P_mg_L	38.88	s.e. 7.67
rep 1 block 3 Subject 5 Time %2014_P_mg_L	-24.75	s.e. 7.67
rep 1 block 4 Subject 10 Time %2014_P_mg_L	-36.68	s.e. 7.67
rep 1 block 4 Subject 11 Time %2013_P_mg_L	-23.02	s.e. 7.67
rep 1 block 4 Subject 11 Time %2014_P_mg_L	45.39	s.e. 7.67

Tables of means

Variate: %2010_P_mg_L,%2011_P_mg_L,%2012_P_mg_L,%2013_P_mg_L,%2014_P_mg_L

Grand mean 34.58

Time	%2010_P_mg_L	%2011_P_mg_L	%2012_P_mg_L	%2013_P_mg_L	%2014_P_mg_L
	24.27	26.60	34.56	38.45	49.02
N_kg_ha	0	80	160	240	
	35.64	33.23	35.11	34.34	
P_kg_ha	0	40	80	120	
	22.66	31.12	38.04	46.51	
L_t_ha	0	2	4	8	
	35.74	32.62	34.41	35.56	
Time	N_kg_ha	0	80	160	240
%2010_P_mg_L		23.88	23.00	23.94	26.28
%2011_P_mg_L		26.38	26.38	24.91	28.75
%2012_P_mg_L		33.28	34.22	37.28	33.47
%2013_P_mg_L		40.94	35.41	40.03	37.44
%2014_P_mg_L		53.75	47.12	49.41	45.78
Time	P_kg_ha	0	40	80	120
%2010_P_mg_L		26.25	23.41	25.50	21.94
%2011_P_mg_L		21.69	25.16	27.75	31.81
%2012_P_mg_L		27.69	33.09	35.41	42.06
%2013_P_mg_L		21.41	33.81	42.50	56.09
%2014_P_mg_L		16.25	40.12	59.03	80.66
N_kg_ha	P_kg_ha	0	40	80	120
0		20.58	32.93	40.28	48.80
80		21.98	26.95	37.90	46.08
160		21.83	35.58	35.90	47.15
240		26.25	29.03	38.08	44.03
Time	L_t_ha	0	2	4	8
%2010_P_mg_L		23.75	22.47	24.50	26.37
%2011_P_mg_L		28.72	26.16	26.25	25.28
%2012_P_mg_L		34.56	33.12	34.44	36.12
%2013_P_mg_L		40.81	35.41	37.75	39.84
%2014_P_mg_L		50.84	45.97	49.09	50.16
N_kg_ha	L_t_ha	0	2	4	8
0		42.92	28.92	37.00	33.72
80		31.32	31.70	34.17	35.70
160		34.60	33.45	34.17	38.23
240		34.10	36.42	32.27	34.57
P_kg_ha	L_t_ha	0	2	4	8
0		21.30	23.73	22.10	23.50
40		34.10	26.57	30.75	33.05
80		36.15	34.02	41.15	40.82
120		51.40	46.17	43.62	44.85

Time	N_kg_ha	P_kg_ha	0	40	80
%2010_P_mg_L	0		22.13	23.00	27.38
	80		23.38	21.00	23.50
	160		22.38	27.63	26.38
	240		37.13	22.00	24.75
%2011_P_mg_L	0		20.25	23.63	28.63
	80		23.38	21.88	27.38
	160		17.88	27.63	25.25
	240		25.25	27.50	29.75
%2012_P_mg_L	0		25.38	30.75	34.50
	80		25.50	29.38	40.63
	160		29.63	42.63	30.88
	240		30.25	29.63	35.63
%2013_P_mg_L	0		19.75	39.13	45.63
	80		21.63	30.25	40.38
	160		22.13	35.50	40.50
	240		22.12	30.38	43.50
%2014_P_mg_L	0		15.38	48.13	65.25
	80		16.00	32.25	57.62
	160		17.13	44.50	56.50
	240		16.50	35.62	56.75

Time	N_kg_ha	P_kg_ha	120
%2010_P_mg_L	0		23.00
	80		24.13
	160		19.38
	240		21.25
%2011_P_mg_L	0		33.00
	80		32.88
	160		28.88
	240		32.50
%2012_P_mg_L	0		42.50
	80		41.38
	160		46.00
	240		38.38
%2013_P_mg_L	0		59.25
	80		49.38
	160		62.00
	240		53.75
%2014_P_mg_L	0		86.25
	80		82.62
	160		79.50
	240		74.25

Time	N_kg_ha	L_t_ha	0	2	4	8
%2010_P_mg_L	0		30.12	21.00	22.00	22.38
	80		21.50	23.38	23.62	23.50
	160		19.00	21.75	29.00	26.00
	240		24.38	23.75	23.38	33.62
%2011_P_mg_L	0		33.25	22.50	28.12	21.63
	80		27.00	28.50	25.75	24.25
	160		22.12	26.50	24.00	27.00
	240		32.50	27.12	27.12	28.25
%2012_P_mg_L	0		37.88	27.63	39.25	28.38
	80		31.25	29.25	37.00	39.38
	160		35.62	39.38	32.00	42.12
	240		33.50	36.25	29.50	34.62
%2013_P_mg_L	0		46.75	32.50	41.12	43.37
	80		33.12	32.00	36.75	39.75

	160		45.62	37.25	37.12	40.13	
	240		37.75	39.87	36.00	36.12	
%2014_P_mg_L	0		66.62	41.00	54.50	52.88	
	80		43.75	45.38	47.75	51.62	
	160		50.62	42.38	48.75	55.88	
	240		42.37	55.12	45.37	40.25	
	Time	P_kg_ha	L_t_ha	0	2	4	8
%2010_P_mg_L		0		20.25	26.25	25.75	32.75
		40		25.75	20.75	21.00	26.12
		80		24.00	21.00	29.75	27.25
		120		25.00	21.87	21.50	19.37
%2011_P_mg_L		0		20.50	24.63	21.00	20.63
		40		29.00	21.75	24.62	25.25
		80		27.25	26.62	29.87	27.25
		120		38.12	31.62	29.50	28.00
%2012_P_mg_L		0		27.50	28.63	25.88	28.75
		40		33.50	26.88	35.12	36.87
		80		30.12	33.37	37.37	40.75
		120		47.12	43.62	39.38	38.13
%2013_P_mg_L		0		21.75	20.63	22.38	20.88
		40		39.00	27.75	31.75	36.75
		80		39.38	40.25	43.37	47.00
		120		63.12	53.00	53.50	54.75
%2014_P_mg_L		0		16.50	18.50	15.50	14.50
		40		43.25	35.75	41.25	40.25
		80		60.00	48.87	65.37	61.87
		120		83.62	80.75	74.25	84.00

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	160	160	160
d.f.	228.09	84	84	84
l.s.d.	2.712	3.636	3.636	3.636

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	40	32
l.s.d.	6.219	6.219	7.273	6.219
d.f.	289.59	289.59	84	289.59

Except when comparing means with the same level(s) of

N_kg_ha	5.424			
d.f.	228.09			
P_kg_ha		5.424		
d.f.		228.09		
L_t_ha				5.424
d.f.				228.09

Table	N_kg_ha	P_kg_ha	Time	Time
	L_t_ha	L_t_ha	N_kg_ha	N_kg_ha
			P_kg_ha	L_t_ha
rep.	40	40	8	8
l.s.d.	7.273	7.273	12.439	12.439
d.f.	84	84	289.59	289.59

Except when comparing means with the same level(s) of

N_kg_ha.P_kg_ha			10.848	
d.f.			228.09	
N_kg_ha.L_t_ha				10.848

d.f. 228.09

Table	Time
	P_kg_ha
	L_t_ha
rep.	8
l.s.d.	12.439
d.f.	289.59
Except when comparing means with the same level(s) of	
P_kg_ha.L_t_ha	10.848
d.f.	228.09

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %2010_P_mg_L,%2011_P_mg_L,%2012_P_mg_L,%2013_P_mg_L,%2014_P_mg_L

Stratum	d.f.	s.e.	cv%
rep	1	3.593	10.4
rep.block	6	3.103	9.0
rep.block.Subject	84	7.314	21.2
rep.block.Subject.Time	364	10.168	29.4

Analysis of variance

Variate: %2010_Ca_mg_L,%2011_Ca_mg_L,%2012_Ca_mg_L,%2013_Ca_mg_L,%2014_Ca_mg_L

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	8.	8.	0.00	
rep.block stratum	6	162734.	27122.	1.30	
rep.block.Subject stratum					
N_kg_ha	3	169757.	56586.	2.72	0.049
P_kg_ha	3	138550.	46183.	2.22	0.092
L_t_ha	3	4422663.	1474221.	70.91	<.001
N_kg_ha.P_kg_ha	9	540351.	60039.	2.89	0.005
N_kg_ha.L_t_ha	9	296107.	32901.	1.58	0.134
P_kg_ha.L_t_ha	9	113071.	12563.	0.60	0.790
Residual	84	1746254.	20789.	3.17	
rep.block.Subject.Time stratum					
d.f. correction factor 0.7525					
Time	4	26260638.	6565159.	1002.00	<.001
Time.N_kg_ha	12	101570.	8464.	1.29	0.241
Time.P_kg_ha	12	127870.	10656.	1.63	0.107
Time.L_t_ha	12	1573015.	131085.	20.01	<.001
Time.N_kg_ha.P_kg_ha	36	239427.	6651.	1.02	0.448
Time.N_kg_ha.L_t_ha	36	253034.	7029.	1.07	0.372
Time.P_kg_ha.L_t_ha	36	253219.	7034.	1.07	0.371
Residual	364	2384955.	6552.		
Total	639	38783224.			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 block 4 Subject 8	-151.1	s.e. 52.2
rep 2 block 4 Subject 1	138.8	s.e. 52.2
rep 1 block 2 Subject 13 Time %2013_Ca_mg_L	185.0	s.e. 61.0
rep 2 block 2 Subject 16 Time %2014_Ca_mg_L	221.9	s.e. 61.0

Tables of means

Variate: %2010_Ca_mg_L,%2011_Ca_mg_L,%2012_Ca_mg_L,%2013_Ca_mg_L,%2014_Ca_mg_L

Grand mean 503.6

Time %2010_Ca_mg_L %2011_Ca_mg_L %2012_Ca_mg_L %2013_Ca_mg_L %2014_Ca_mg_L

	160.1	383.6	646.9	642.3	685.1
N_kg_ha	0	80	160	240	
	513.4	509.0	516.2	475.7	
P_kg_ha	0	40	80	120	
	505.2	503.6	523.5	482.0	
L_t_ha	0	2	4	8	
	405.6	444.9	548.0	615.9	
Time	N_kg_ha	0	80	160	240
%2010_Ca_mg_L		148.5	159.3	171.3	161.2
%2011_Ca_mg_L		381.4	396.6	393.0	363.3
%2012_Ca_mg_L		657.5	665.1	665.5	599.5
%2013_Ca_mg_L		669.8	633.4	661.4	604.6
%2014_Ca_mg_L		709.8	690.7	690.0	650.2
Time	P_kg_ha	0	40	80	120
%2010_Ca_mg_L		162.6	158.6	161.5	157.6
%2011_Ca_mg_L		383.1	385.9	378.6	386.7
%2012_Ca_mg_L		653.6	644.1	693.2	596.7
%2013_Ca_mg_L		650.7	637.2	669.7	611.6
%2014_Ca_mg_L		676.1	692.3	714.7	657.5
N_kg_ha	P_kg_ha	0	40	80	120
0		524.7	507.5	506.8	514.6
80		455.1	516.9	580.4	483.6
160		519.7	509.9	565.0	470.3
240		521.4	480.2	441.9	459.6
Time	L_t_ha	0	2	4	8
%2010_Ca_mg_L		164.9	161.1	159.9	154.3
%2011_Ca_mg_L		304.4	332.8	415.3	481.8
%2012_Ca_mg_L		467.4	558.6	741.6	820.0
%2013_Ca_mg_L		518.2	560.6	703.5	787.0
%2014_Ca_mg_L		573.0	611.3	719.8	836.5
N_kg_ha	L_t_ha	0	2	4	8
0		383.5	484.8	549.3	636.0
80		420.5	430.6	569.0	616.0
160		434.2	435.0	592.6	603.2
240		384.2	429.1	481.2	608.5
P_kg_ha	L_t_ha	0	2	4	8
0		400.7	448.3	547.1	624.7
40		397.6	446.2	536.3	634.4
80		438.6	481.8	554.4	619.4
120		385.5	403.1	554.2	585.1
Time	N_kg_ha	P_kg_ha	0	40	80
%2010_Ca_mg_L	0		169.5	126.6	147.5
	80		145.2	166.0	164.4
	160		158.6	181.9	186.0
	240		176.9	159.8	148.2
%2011_Ca_mg_L	0		392.9	401.8	333.4
	80		341.8	402.4	436.8
	160		419.1	360.4	419.8
	240		378.8	379.0	324.6
%2012_Ca_mg_L	0		676.8	668.9	661.1

	80	571.0	664.2	813.9
	160	685.0	663.2	718.2
	240	681.8	580.1	579.4
%2013_Ca_mg_L	0	682.5	661.4	669.4
	80	598.1	619.9	718.4
	160	635.6	658.9	733.6
	240	686.6	608.8	557.4
%2014_Ca_mg_L	0	702.0	678.8	722.4
	80	619.6	731.9	768.9
	160	700.0	685.4	767.5
	240	682.9	673.1	599.9

Time	N_kg_ha	P_kg_ha	120		
%2010_Ca_mg_L	0		150.2		
	80		161.4		
	160		158.9		
	240		159.8		
%2011_Ca_mg_L	0		397.8		
	80		405.5		
	160		372.6		
	240		370.9		
%2012_Ca_mg_L	0		623.4		
	80		611.2		
	160		595.5		
	240		556.6		
%2013_Ca_mg_L	0		665.9		
	80		597.4		
	160		617.6		
	240		565.6		
%2014_Ca_mg_L	0		735.9		
	80		642.3		
	160		607.0		
	240		644.9		

Time	N_kg_ha	L_t_ha	0	2	4
%2010_Ca_mg_L	0		152.0	149.3	152.8
	80		152.3	153.0	171.3
	160		179.1	174.8	174.5
	240		176.3	167.3	141.1
%2011_Ca_mg_L	0		263.9	349.9	402.2
	80		324.1	328.4	456.6
	160		320.8	337.8	420.6
	240		309.0	315.1	381.8
%2012_Ca_mg_L	0		452.0	638.6	753.8
	80		529.4	546.1	735.0
	160		486.8	526.7	826.9
	240		401.5	523.0	650.6
%2013_Ca_mg_L	0		502.6	634.5	698.8
	80		515.9	524.2	715.2
	160		570.6	541.0	782.0
	240		483.8	542.6	617.9
%2014_Ca_mg_L	0		546.8	651.9	739.0
	80		581.0	601.1	766.6
	160		613.6	594.6	759.0
	240		550.5	597.6	614.6

Time	N_kg_ha	L_t_ha	8
%2010_Ca_mg_L	0		139.9
	80		160.5
	160		157.0

	240	160.0
%2011_Ca_mg_L	0	509.8
	80	477.3
	160	492.8
	240	447.4
%2012_Ca_mg_L	0	785.8
	80	849.9
	160	821.6
	240	822.8
%2013_Ca_mg_L	0	843.3
	80	778.4
	160	752.1
	240	774.1
%2014_Ca_mg_L	0	901.4
	80	813.9
	160	792.6
	240	838.0

Time	P_kg_ha	L_t_ha	0	2	4
%2010_Ca_mg_L	0		158.3	175.0	162.9
	40		165.3	155.0	153.5
	80		171.5	163.0	163.4
	120		164.6	151.3	159.9
%2011_Ca_mg_L	0		318.1	324.1	396.8
	40		286.4	360.4	428.8
	80		320.3	338.5	396.0
	120		293.0	308.1	439.8
%2012_Ca_mg_L	0		476.0	571.7	733.1
	40		469.5	543.4	731.6
	80		524.0	636.5	744.9
	120		400.1	482.9	756.6
%2013_Ca_mg_L	0		484.9	561.7	751.6
	40		500.8	548.8	649.0
	80		529.6	615.2	733.5
	120		557.6	516.6	679.8
%2014_Ca_mg_L	0		566.4	609.1	691.3
	40		566.0	623.5	718.6
	80		647.4	655.8	734.1
	120		512.1	556.9	735.3

Time	P_kg_ha	L_t_ha	8
%2010_Ca_mg_L	0		154.1
	40		160.5
	80		148.3
	120		154.5
%2011_Ca_mg_L	0		493.5
	40		468.0
	80		459.8
	120		505.9
%2012_Ca_mg_L	0		833.6
	40		832.0
	80		867.2
	120		747.1
%2013_Ca_mg_L	0		804.6
	40		850.4
	80		800.4
	120		692.5
%2014_Ca_mg_L	0		837.8
	40		861.0
	80		821.4

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	160	160	160
d.f.	273.91	84	84	84
l.s.d.	20.93	32.06	32.06	32.06

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	40	32
l.s.d.	50.12	50.12	64.11	50.12
d.f.	288.62	288.62	84	288.62

Except when comparing means with the same level(s) of

N_kg_ha	41.85			
d.f.	273.91			
P_kg_ha		41.85		
d.f.		273.91		
L_t_ha				41.85
d.f.				273.91

Table	N_kg_ha	P_kg_ha	Time	Time
	L_t_ha	L_t_ha	N_kg_ha	N_kg_ha
			P_kg_ha	L_t_ha
rep.	40	40	8	8
l.s.d.	64.11	64.11	100.24	100.24
d.f.	84	84	288.62	288.62

Except when comparing means with the same level(s) of

N_kg_ha.P_kg_ha		83.71		
d.f.		273.91		
N_kg_ha.L_t_ha				83.71
d.f.				273.91

Table	Time
	P_kg_ha
	L_t_ha
rep.	8
l.s.d.	100.24
d.f.	288.62

Except when comparing means with the same level(s) of

P_kg_ha.L_t_ha	83.71
d.f.	273.91

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %2010_Ca_mg_L,%2011_Ca_mg_L,%2012_Ca_mg_L,%2013_Ca_mg_L,%2014_Ca_mg_L

Stratum	d.f.	s.e.	cv%
rep	1	0.16	0.0
rep.block	6	18.41	3.7
rep.block.Subject	84	64.48	12.8
rep.block.Subject.Time	364	80.94	16.1

Analysis of variance

Variate:

%2010_Mg_mg_L,%2011_Mg_mg_L,%2012_Mg_mg_L,%2013_Mg_mg_L,%2014_Mg_mg_L

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	6181.4	6181.4	1.96	
rep.block stratum	6	18882.7	3147.1	4.45	
rep.block.Subject stratum					
N_kg_ha	3	4003.9	1334.6	1.89	0.138
P_kg_ha	3	5124.1	1708.0	2.41	0.072
L_t_ha	3	79598.6	26532.9	37.50	<.001
N_kg_ha.P_kg_ha	9	13208.1	1467.6	2.07	0.041
N_kg_ha.L_t_ha	9	10322.9	1147.0	1.62	0.122
P_kg_ha.L_t_ha	9	3748.8	416.5	0.59	0.803
Residual	84	59439.6	707.6	2.18	
rep.block.Subject.Time stratum					
d.f. correction factor 0.8455					
Time	4	643134.1	160783.5	495.64	<.001
Time.N_kg_ha	12	4828.2	402.4	1.24	0.264
Time.P_kg_ha	12	7520.6	626.7	1.93	0.040
Time.L_t_ha	12	27822.1	2318.5	7.15	<.001
Time.N_kg_ha.P_kg_ha	36	10247.0	284.6	0.88	0.657
Time.N_kg_ha.L_t_ha	36	10944.2	304.0	0.94	0.566
Time.P_kg_ha.L_t_ha	36	8898.0	247.2	0.76	0.816
Residual	364	118079.9	324.4		
Total	639	1031984.1			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 block 4 Subject 6 -24.41 s.e. 9.64

Tables of means

Variate:

%2010_Mg_mg_L,%2011_Mg_mg_L,%2012_Mg_mg_L,%2013_Mg_mg_L,%2014_Mg_mg_L

Grand mean 100.55

Time	%2010_Mg_mg_L	%2011_Mg_mg_L	%2012_Mg_mg_L	%2013_Mg_mg_L	%2014_Mg_mg_L
	48.40	79.12	122.43	122.62	130.20
N_kg_ha	0	80	160	240	
	102.56	101.56	101.84	96.27	

P_kg_ha	0	40	80	120	
	102.72	100.43	103.08	95.98	
L_t_ha	0	2	4	8	
	86.88	93.19	106.88	115.26	
Time	N_kg_ha	0	80	160	240
%2010_Mg_mg_L		47.66	46.03	52.44	47.47
%2011_Mg_mg_L		77.31	81.56	82.56	75.03
%2012_Mg_mg_L		126.19	125.59	122.81	115.12
%2013_Mg_mg_L		128.06	120.84	125.69	115.91
%2014_Mg_mg_L		133.56	133.75	125.69	127.81
Time	P_kg_ha	0	40	80	120
%2010_Mg_mg_L		47.00	48.56	49.81	48.22
%2011_Mg_mg_L		79.09	78.41	79.09	79.88
%2012_Mg_mg_L		123.97	118.56	130.12	117.06
%2013_Mg_mg_L		125.91	121.97	125.41	117.22
%2014_Mg_mg_L		137.66	134.66	130.97	117.53
N_kg_ha	P_kg_ha	0	40	80	120
0		107.50	99.98	100.50	102.25
80		95.25	103.18	111.42	96.38
160		103.00	101.43	109.42	93.50
240		105.15	97.15	90.97	91.80
Time	L_t_ha	0	2	4	8
%2010_Mg_mg_L		48.12	48.41	48.47	48.59
%2011_Mg_mg_L		68.16	70.56	83.44	94.31
%2012_Mg_mg_L		96.16	111.12	134.34	148.09
%2013_Mg_mg_L		106.00	113.12	133.66	137.72
%2014_Mg_mg_L		115.97	122.75	134.50	147.59
N_kg_ha	L_t_ha	0	2	4	8
0		82.58	99.45	106.92	121.28
80		89.88	89.12	112.10	115.12
160		90.23	96.12	111.73	109.28
240		84.85	88.08	96.78	115.38
P_kg_ha	L_t_ha	0	2	4	8
0		90.45	96.77	108.15	115.52
40		85.00	93.88	106.80	116.05
80		92.28	97.97	105.85	116.22
120		79.80	84.15	106.73	113.25
Time	N_kg_ha	P_kg_ha	0	40	80
%2010_Mg_mg_L	0		52.75	44.25	45.62
	80		42.12	46.38	48.62
	160		45.75	56.87	55.12
	240		47.38	46.75	49.88
%2011_Mg_mg_L	0		80.62	77.75	71.00
	80		73.62	80.62	87.62
	160		85.62	78.62	87.12
	240		76.50	76.62	70.62
%2012_Mg_mg_L	0		131.25	123.62	132.62
	80		112.00	124.75	143.25
	160		121.38	120.88	132.62
	240		131.25	105.00	112.00
%2013_Mg_mg_L	0		132.38	125.00	122.38

	80	114.62	118.25	134.00
	160	128.00	128.12	135.12
	240	128.62	116.50	110.12
%2014_Mg_mg_L	0	140.50	129.25	130.88
	80	133.88	145.88	143.62
	160	134.25	122.63	137.13
	240	142.00	140.88	112.25

Time	N_kg_ha	P_kg_ha	120		
%2010_Mg_mg_L	0		48.00		
	80		47.00		
	160		52.00		
	240		45.88		
%2011_Mg_mg_L	0		79.88		
	80		84.38		
	160		78.87		
	240		76.38		
%2012_Mg_mg_L	0		117.25		
	80		122.38		
	160		116.37		
	240		112.25		
%2013_Mg_mg_L	0		132.50		
	80		116.50		
	160		111.50		
	240		108.38		
%2014_Mg_mg_L	0		133.63		
	80		111.63		
	160		108.75		
	240		116.12		

Time	N_kg_ha	L_t_ha	0	2	4
%2010_Mg_mg_L	0		47.38	47.38	44.50
	80		43.12	41.25	48.12
	160		52.62	53.25	55.25
	240		49.38	51.75	46.00
%2011_Mg_mg_L	0		58.88	70.38	79.88
	80		70.38	67.50	92.50
	160		71.25	76.88	86.38
	240		72.12	67.50	75.00
%2012_Mg_mg_L	0		96.50	124.50	138.62
	80		107.50	107.88	136.38
	160		98.00	112.25	141.12
	240		82.62	99.88	121.25
%2013_Mg_mg_L	0		102.12	123.38	134.75
	80		107.62	105.88	135.38
	160		112.12	116.38	141.88
	240		102.12	106.88	122.63
%2014_Mg_mg_L	0		108.00	131.63	136.88
	80		120.75	123.13	148.12
	160		117.13	121.88	134.00
	240		118.00	114.38	119.00

Time	N_kg_ha	L_t_ha	8		
%2010_Mg_mg_L	0		51.37		
	80		51.62		
	160		48.62		
	240		42.75		
%2011_Mg_mg_L	0		100.12		
	80		95.87		
	160		95.75		

	240	85.50
%2012_Mg_mg_L	0	145.12
	80	150.63
	160	139.88
	240	156.75
%2013_Mg_mg_L	0	152.00
	80	134.50
	160	132.38
	240	132.00
%2014_Mg_mg_L	0	157.75
	80	143.00
	160	129.75
	240	159.88

Time	P_kg_ha	L_t_ha	0	2	4
%2010_Mg_mg_L	0		46.50	49.50	46.50
	40		47.88	49.25	47.25
	80		51.50	48.37	51.50
	120		46.62	46.50	48.62
%2011_Mg_mg_L	0		71.50	71.62	77.88
	40		62.38	73.62	87.38
	80		74.12	70.88	79.25
	120		64.62	66.12	89.25
%2012_Mg_mg_L	0		98.38	115.25	134.12
	40		98.38	105.12	129.50
	80		104.50	121.00	135.00
	120		83.38	103.12	138.75
%2013_Mg_mg_L	0		107.50	118.75	139.25
	40		104.75	105.25	130.88
	80		105.75	122.12	134.62
	120		106.00	106.38	129.88
%2014_Mg_mg_L	0		128.38	128.75	143.00
	40		111.63	136.12	139.00
	80		125.50	127.50	128.88
	120		98.38	98.62	127.13

Time	P_kg_ha	L_t_ha	8
%2010_Mg_mg_L	0		45.50
	40		49.88
	80		47.88
	120		51.12
%2011_Mg_mg_L	0		95.38
	40		90.25
	80		92.12
	120		99.50
%2012_Mg_mg_L	0		148.13
	40		141.25
	80		160.00
	120		143.00
%2013_Mg_mg_L	0		138.13
	40		147.00
	80		139.12
	120		126.63
%2014_Mg_mg_L	0		150.50
	40		151.88
	80		142.00
	120		146.00

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	160	160	160
d.f.	307.76	84	84	84
l.s.d.	4.562	5.914	5.914	5.914

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	40	32
l.s.d.	10.141	10.141	11.829	10.141
d.f.	351.72	351.72	84	351.72

Except when comparing means with the same level(s) of

N_kg_ha	9.125			
d.f.	307.76			
P_kg_ha		9.125		
d.f.		307.76		
L_t_ha				9.125
d.f.				307.76

Table	N_kg_ha	P_kg_ha	Time	Time
	L_t_ha	L_t_ha	N_kg_ha	N_kg_ha
			P_kg_ha	L_t_ha
rep.	40	40	8	8
l.s.d.	11.829	11.829	20.281	20.281
d.f.	84	84	351.72	351.72

Except when comparing means with the same level(s) of

N_kg_ha.P_kg_ha	18.249		
d.f.	307.76		
N_kg_ha.L_t_ha			18.249
d.f.			307.76

Table	Time
	P_kg_ha
	L_t_ha
rep.	8
l.s.d.	20.281
d.f.	351.72

Except when comparing means with the same level(s) of

P_kg_ha.L_t_ha	18.249
d.f.	307.76

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate:

%2010_Mg_mg_L,%2011_Mg_mg_L,%2012_Mg_mg_L,%2013_Mg_mg_L,%2014_Mg_mg_L

Stratum	d.f.	s.e.	cv%
rep	1	4.395	4.4
rep.block	6	6.272	6.2
rep.block.Subject	84	11.896	11.8
rep.block.Subject.Time	364	18.011	17.9

Analysis of variance

Variate: %2010_pH_KCL,%2011_pH_KCL,%2012_pH_KCL,%2013_pH_KCL,%2014_pH_KCL

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	2.1068	2.1068	3.58	
rep.block stratum	6	3.5280	0.5880	1.36	
rep.block.Subject stratum					
N_kg_ha	3	7.5285	2.5095	5.80	0.001
P_kg_ha	3	6.4997	2.1666	5.01	0.003
L_t_ha	3	93.1191	31.0397	71.71	<.001
N_kg_ha.P_kg_ha	9	4.7265	0.5252	1.21	0.298
N_kg_ha.L_t_ha	9	4.6654	0.5184	1.20	0.307
P_kg_ha.L_t_ha	9	2.0061	0.2229	0.51	0.860
Residual	84	36.3579	0.4328	3.24	
rep.block.Subject.Time stratum					
d.f. correction factor 0.6607					
Time	4	327.6488	81.9122	612.58	<.001
Time.N_kg_ha	12	6.3598	0.5300	3.96	<.001
Time.P_kg_ha	12	5.7740	0.4812	3.60	<.001
Time.L_t_ha	12	37.2731	3.1061	23.23	<.001
Time.N_kg_ha.P_kg_ha	36	3.9525	0.1098	0.82	0.707
Time.N_kg_ha.L_t_ha	36	6.4305	0.1786	1.34	0.142
Time.P_kg_ha.L_t_ha	36	4.1026	0.1140	0.85	0.666
Residual	364	48.6731	0.1337		
Total	639	600.7524			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 block 4 Subject 8	-0.633	s.e. 0.238
rep 1 block 3 Subject 14 Time %2013_pH_KCL	0.941	s.e. 0.276
rep 1 block 4 Subject 3 Time %2013_pH_KCL	1.412	s.e. 0.276
rep 2 block 4 Subject 7 Time %2014_pH_KCL	0.967	s.e. 0.276

Tables of means

Variate: %2010_pH_KCL,%2011_pH_KCL,%2012_pH_KCL,%2013_pH_KCL,%2014_pH_KCL

Grand mean 4.952

Time	%2010_pH_KCL	%2011_pH_KCL	%2012_pH_KCL	%2013_pH_KCL	%2014_pH_KCL
	3.857	4.349	5.425	5.674	5.453
N_kg_ha	0	80	160	240	
	5.083	4.986	4.954	4.783	
P_kg_ha	0	40	80	120	
	5.042	4.985	4.998	4.781	
L_t_ha	0	2	4	8	
	4.465	4.718	5.186	5.437	
Time	N_kg_ha	0	80	160	240
%2010_pH_KCL		3.848	3.867	3.848	3.864
%2011_pH_KCL		4.340	4.430	4.353	4.272
%2012_pH_KCL		5.489	5.461	5.537	5.213
%2013_pH_KCL		6.014	5.649	5.622	5.411
%2014_pH_KCL		5.725	5.522	5.412	5.153
Time	P_kg_ha	0	40	80	120
%2010_pH_KCL		3.856	3.857	3.861	3.853
%2011_pH_KCL		4.358	4.375	4.303	4.359
%2012_pH_KCL		5.505	5.416	5.599	5.181
%2013_pH_KCL		5.843	5.771	5.771	5.309
%2014_pH_KCL		5.646	5.506	5.458	5.202
N_kg_ha	P_kg_ha	0	40	80	120
0		5.235	5.129	5.019	4.951
80		4.910	5.021	5.210	4.802
160		5.060	4.984	5.071	4.703
240		4.962	4.808	4.694	4.668
Time	L_t_ha	0	2	4	8
%2010_pH_KCL		3.865	3.861	3.848	3.853
%2011_pH_KCL		4.082	4.177	4.446	4.689
%2012_pH_KCL		4.606	5.038	5.918	6.139
%2013_pH_KCL		4.955	5.263	6.034	6.443
%2014_pH_KCL		4.818	5.249	5.683	6.062
N_kg_ha	L_t_ha	0	2	4	8
0		4.491	4.962	5.307	5.573
80		4.589	4.754	5.186	5.414
160		4.432	4.600	5.374	5.412
240		4.349	4.556	4.876	5.350
P_kg_ha	L_t_ha	0	2	4	8
0		4.480	4.840	5.273	5.574
40		4.521	4.721	5.186	5.513
80		4.541	4.803	5.150	5.501
120		4.319	4.508	5.135	5.161
Time	N_kg_ha	P_kg_ha	0	40	80
%2010_pH_KCL	0		3.854	3.839	3.851
	80		3.866	3.858	3.873

	160	3.844	3.864	3.851
	240	3.860	3.869	3.868
%2011_pH_KCL	0	4.373	4.438	4.200
	80	4.276	4.479	4.438
	160	4.426	4.274	4.416
	240	4.358	4.310	4.156
%2012_pH_KCL	0	5.599	5.569	5.509
	80	5.266	5.386	5.983
	160	5.719	5.588	5.653
	240	5.436	5.121	5.254
%2013_pH_KCL	0	6.454	6.008	5.911
	80	5.491	5.758	6.070
	160	5.729	5.751	5.821
	240	5.700	5.569	5.283
%2014_pH_KCL	0	5.898	5.790	5.624
	80	5.650	5.624	5.689
	160	5.581	5.443	5.613
	240	5.455	5.169	4.909

	Time	N_kg_ha	P_kg_ha	120
%2010_pH_KCL		0		3.849
		80		3.870
		160		3.833
		240		3.860
%2011_pH_KCL		0		4.351
		80		4.528
		160		4.295
		240		4.264
%2012_pH_KCL		0		5.281
		80		5.210
		160		5.189
		240		5.043
%2013_pH_KCL		0		5.683
		80		5.276
		160		5.186
		240		5.093
%2014_pH_KCL		0		5.589
		80		5.126
		160		5.011
		240		5.080

	Time	N_kg_ha	L_t_ha	0	2	4	8
%2010_pH_KCL		0		3.868	3.850	3.841	3.834
		80		3.878	3.879	3.864	3.846
		160		3.835	3.861	3.828	3.868
		240		3.879	3.855	3.858	3.865
%2011_pH_KCL		0		3.998	4.173	4.330	4.861
		80		4.154	4.293	4.628	4.646
		160		4.086	4.141	4.478	4.706
		240		4.091	4.103	4.350	4.544
%2012_pH_KCL		0		4.674	5.333	5.954	5.998
		80		4.833	4.968	5.798	6.248
		160		4.581	4.974	6.364	6.229
		240		4.338	4.876	5.558	6.083
%2013_pH_KCL		0		4.978	5.826	6.583	6.669
		80		5.126	5.193	5.889	6.388
		160		4.846	5.038	6.249	6.355
		240		4.869	4.998	5.418	6.360
%2014_pH_KCL		0		4.939	5.629	5.829	6.504
		80		4.955	5.438	5.754	5.943

	160	240	4.810	4.984	5.950	5.904
	160	240	4.569	4.948	5.199	5.898
Time	P_kg_ha	L_t_ha	0	2	4	8
%2010_pH_KCL	0		3.861	3.863	3.856	3.844
	40		3.871	3.866	3.845	3.846
	80		3.885	3.861	3.839	3.858
	120		3.841	3.855	3.850	3.865
%2011_pH_KCL	0		4.103	4.130	4.404	4.796
	40		4.078	4.244	4.506	4.673
	80		4.130	4.143	4.375	4.563
	120		4.019	4.193	4.500	4.726
%2012_pH_KCL	0		4.605	5.228	5.944	6.244
	40		4.641	4.958	5.868	6.198
	80		4.808	5.283	5.918	6.390
	120		4.371	4.683	5.944	5.725
%2013_pH_KCL	0		4.875	5.413	6.410	6.676
	40		5.194	5.266	5.939	6.686
	80		4.933	5.510	6.005	6.638
	120		4.818	4.865	5.784	5.771
%2014_pH_KCL	0		4.955	5.566	5.751	6.311
	40		4.820	5.270	5.774	6.161
	80		4.950	5.216	5.611	6.056
	120		4.548	4.945	5.595	5.719

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	160	160	160
d.f.	240.49	84	84	84
l.s.d.	0.0967	0.1463	0.1463	0.1463

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	40	32
l.s.d.	0.2325	0.2325	0.2925	0.2325
d.f.	273.83	273.83	84	273.83

Except when comparing means with the same level(s) of

N_kg_ha	0.1933			
d.f.	240.49			
P_kg_ha		0.1933		
d.f.		240.49		
L_t_ha			0.1933	
d.f.			240.49	

Table	N_kg_ha	P_kg_ha	Time	Time
	L_t_ha	L_t_ha	N_kg_ha	N_kg_ha
			P_kg_ha	L_t_ha
rep.	40	40	8	8
l.s.d.	0.2925	0.2925	0.4649	0.4649
d.f.	84	84	273.83	273.83

Except when comparing means with the same level(s) of

N_kg_ha.P_kg_ha	0.3867			
d.f.	240.49			
N_kg_ha.L_t_ha			0.3867	
d.f.			240.49	

Table	Time
	P_kg_ha

	L_t_ha
rep.	8
l.s.d.	0.4649
d.f.	273.83
Except when comparing means with the same level(s) of	
P_kg_ha.L_t_ha	0.3867
d.f.	240.49

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %2010_pH_KCL,%2011_pH_KCL,%2012_pH_KCL,%2013_pH_KCL,%2014_pH_KCL

Stratum	d.f.	s.e.	cv%
rep	1	0.0811	1.6
rep.block	6	0.0857	1.7
rep.block.Subject	84	0.2942	5.9
rep.block.Subject.Time	364	0.3657	7.4

Appendix 3.8: Chapter 3 (N x P x L trial) leaf statistical analysis

Analysis of variance

Variate:

Ca_%_2012_1st,Ca_%_2012_2nd,Ca_%_2013_1st,Ca_%_2013_2nd,Ca_%_2014_1st,Ca_%_2014_2nd

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	0.08028	0.08028	0.87	
rep.block stratum	6	0.55440	0.09240	2.76	
rep.block.Subject stratum					
N_kg_ha	3	0.81743	0.27248	8.13	<.001
P_kg_ha	3	0.03459	0.01153	0.34	0.793
L_t_ha	3	4.60917	1.53639	45.87	<.001
N_kg_ha.P_kg_ha	9	0.52447	0.05827	1.74	0.093
N_kg_ha.L_t_ha	9	0.13261	0.01473	0.44	0.910
P_kg_ha.L_t_ha	9	0.30673	0.03408	1.02	0.433
Residual	84	2.81367	0.03350	1.38	
rep.block.Subject.Time stratum					
d.f. correction factor 0.8185					
Time	5	45.98227	9.19645	379.93	<.001
Time.N_kg_ha	15	0.61450	0.04097	1.69	0.065
Time.P_kg_ha	15	0.43904	0.02927	1.21	0.273
Time.L_t_ha	15	1.22195	0.08146	3.37	<.001
Time.N_kg_ha.P_kg_ha	45	0.77942	0.01732	0.72	0.892
Time.N_kg_ha.L_t_ha	45	0.96709	0.02149	0.89	0.660
Time.P_kg_ha.L_t_ha	45	0.75681	0.01682	0.69	0.911
Residual	455	11.01362	0.02421		
Total	767	71.64806			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 block 2 Subject 2	0.1587	s.e. 0.0605
rep 2 block 1 Subject 15 Time Ca_%_2014_1st	0.3710	s.e. 0.1198
rep 2 block 2 Subject 2 Time Ca_%_2013_1st	-0.3762	s.e. 0.1198

Tables of means

Variate:

Ca_%_2012_1st,Ca_%_2012_2nd,Ca_%_2013_1st,Ca_%_2013_2nd,Ca_%_2014_1st,Ca_%_2014_2nd

Grand mean 0.9580

Time	Ca_%_2012_1st	Ca_%_2012_2nd	Ca_%_2013_1st	Ca_%_2013_2nd	Ca_%_2014_1st
	0.5610	0.9288	1.0599	1.3721	0.9993

Time	Ca_%_2014_2nd
	0.8271

N_kg_ha	0	80	160	240
	1.0035	0.9654	0.9509	0.9124

P_kg_ha	0	40	80	120
	0.9649	0.9574	0.9625	0.9474

L_t_ha	0	2	4	8
	0.8553	0.9120	1.0209	1.0440

Time	N_kg_ha	0	80	160	240
Ca_%_2012_1st		0.5662	0.5476	0.5830	0.5470
Ca_%_2012_2nd		0.9593	0.9378	0.9211	0.8970
Ca_%_2013_1st		1.1549	1.1083	1.0058	0.9707
Ca_%_2013_2nd		1.3873	1.4083	1.3703	1.3226
Ca_%_2014_1st		1.0951	0.9694	0.9856	0.9473
Ca_%_2014_2nd		0.8580	0.8212	0.8395	0.7896

Time	P_kg_ha	0	40	80	120
Ca_%_2012_1st		0.5775	0.5627	0.5462	0.5574
Ca_%_2012_2nd		0.9434	0.9308	0.9263	0.9148
Ca_%_2013_1st		1.0015	1.0945	1.1118	1.0319
Ca_%_2013_2nd		1.3666	1.3698	1.3652	1.3869
Ca_%_2014_1st		1.0533	0.9655	1.0079	0.9707
Ca_%_2014_2nd		0.8469	0.8210	0.8177	0.8227

N_kg_ha	P_kg_ha	0	40	80	120
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0	1.0365	1.0454	0.9510	0.9811
80	0.9583	0.9461	1.0022	0.9552
160	0.9575	0.9243	0.9953	0.9265
240	0.9073	0.9138	0.9015	0.9268

Time	L_t_ha	0	2	4	8
Ca_%_2012_1st		0.5210	0.5464	0.6004	0.5760
Ca_%_2012_2nd		0.8025	0.9061	0.9853	1.0214
Ca_%_2013_1st		0.9184	0.9584	1.1961	1.1669
Ca_%_2013_2nd		1.2063	1.3007	1.4555	1.5260
Ca_%_2014_1st		0.9058	0.9737	1.0483	1.0696
Ca_%_2014_2nd		0.7778	0.7868	0.8397	0.9040

N_kg_ha	L_t_ha	0	2	4	8
0		0.8697	0.9556	1.0804	1.1082
80		0.8803	0.9064	1.0200	1.0550
160		0.8553	0.9057	1.0092	1.0334
240		0.8159	0.8803	0.9740	0.9793

P_kg_ha	L_t_ha	0	2	4	8
0		0.8361	0.9104	1.0180	1.0951
40		0.8467	0.9359	1.0223	1.0246
80		0.8960	0.9120	1.0250	1.0169
120		0.8423	0.8897	1.0183	1.0393

Time	N_kg_ha	P_kg_ha	0	40	80
Ca_%_2012_1st	0		0.6002	0.6651	0.4892
	80		0.6053	0.5223	0.5459
	160		0.5754	0.5065	0.6637
	240		0.5293	0.5568	0.4859
Ca_%_2012_2nd	0		0.9636	0.9900	0.9349
	80		0.9200	0.9499	0.9957
	160		0.9385	0.8987	0.9260
	240		0.9515	0.8845	0.8486
Ca_%_2013_1st	0		1.0952	1.2752	1.1127
	80		1.0341	1.0271	1.2502
	160		0.9347	1.0895	1.0811
	240		0.9419	0.9863	1.0031
Ca_%_2013_2nd	0		1.4001	1.4136	1.2964
	80		1.3586	1.4258	1.4203
	160		1.4190	1.2955	1.4081
	240		1.2889	1.3445	1.3358
Ca_%_2014_1st	0		1.2544	1.0437	1.0546
	80		0.9839	0.9508	0.9809
	160		1.0205	0.9331	1.0526
	240		0.9543	0.9345	0.9436
Ca_%_2014_2nd	0		0.9053	0.8846	0.8180
	80		0.8477	0.8005	0.8202
	160		0.8567	0.8228	0.8401
	240		0.7781	0.7761	0.7923

Time	N_kg_ha	P_kg_ha	120
Ca_%_2012_1st	0		0.5104
	80		0.5169
	160		0.5864
	240		0.6160
Ca_%_2012_2nd	0		0.9488
	80		0.8855
	160		0.9214
	240		0.9035

Ca_%_2013_1st	0	1.1365
	80	1.1219
	160	0.9177
	240	0.9516
Ca_%_2013_2nd	0	1.4390
	80	1.4286
	160	1.3588
	240	1.3212
Ca_%_2014_1st	0	1.0279
	80	0.9620
	160	0.9362
	240	0.9566
Ca_%_2014_2nd	0	0.8241
	80	0.8165
	160	0.8387
	240	0.8118

Time	N_kg_ha	L_t_ha	0	2	4
Ca_%_2012_1st	0		0.4705	0.5454	0.5844
	80		0.5099	0.5456	0.5805
	160		0.5480	0.5079	0.7197
	240		0.5556	0.5867	0.5169
Ca_%_2012_2nd	0		0.8462	0.9242	1.0216
	80		0.8166	0.9565	0.9628
	160		0.7929	0.8951	0.9891
	240		0.7544	0.8487	0.9678
Ca_%_2013_1st	0		1.0763	1.0243	1.3100
	80		0.9866	0.9485	1.2325
	160		0.7844	0.9507	1.1253
	240		0.8262	0.9099	1.1167
Ca_%_2013_2nd	0		1.1655	1.3488	1.4650
	80		1.2501	1.2900	1.5363
	160		1.2964	1.2981	1.3972
	240		1.1134	1.2658	1.4235
Ca_%_2014_1st	0		0.8986	1.0433	1.2269
	80		0.9349	0.9289	0.9862
	160		0.9109	0.9798	0.9722
	240		0.8787	0.9428	1.0077
Ca_%_2014_2nd	0		0.7610	0.8477	0.8748
	80		0.7838	0.7691	0.8215
	160		0.7995	0.8022	0.8515
	240		0.7670	0.7280	0.8113

Time	N_kg_ha	L_t_ha	8
Ca_%_2012_1st	0		0.6645
	80		0.5544
	160		0.5564
	240		0.5287
Ca_%_2012_2nd	0		1.0454
	80		1.0153
	160		1.0075
	240		1.0172
Ca_%_2013_1st	0		1.2089
	80		1.2658
	160		1.1627
	240		1.0301
Ca_%_2013_2nd	0		1.5699
	80		1.5568
	160		1.4896
	240		1.4876

Ca_%_2014_1st	0	1.2117
	80	1.0275
	160	1.0794
	240	0.9598
Ca_%_2014_2nd	0	0.9485
	80	0.9104
	160	0.9049
	240	0.8521

Time	P_kg_ha	L_t_ha	0	2	4
Ca_%_2012_1st	0		0.5389	0.5568	0.5829
	40		0.4747	0.5811	0.6053
	80		0.5360	0.5311	0.6006
	120		0.5345	0.5165	0.6127
Ca_%_2012_2nd	0		0.8064	0.9416	0.9698
	40		0.7985	0.9098	0.9842
	80		0.8278	0.9099	0.9949
	120		0.7774	0.8631	0.9922
Ca_%_2013_1st	0		0.8943	0.9065	1.1297
	40		0.9586	1.0517	1.1785
	80		0.9996	0.9374	1.2689
	120		0.8210	0.9379	1.2073
Ca_%_2013_2nd	0		1.1839	1.2284	1.4731
	40		1.1716	1.3296	1.5024
	80		1.2410	1.3176	1.4593
	120		1.2290	1.3272	1.3872
Ca_%_2014_1st	0		0.8710	1.0316	1.0840
	40		0.8897	0.9237	1.0706
	80		0.9440	1.0211	1.0086
	120		0.9184	0.9186	1.0297
Ca_%_2014_2nd	0		0.7223	0.7974	0.8682
	40		0.7874	0.8197	0.7925
	80		0.8278	0.7549	0.8179
	120		0.7739	0.7750	0.8804

Time	P_kg_ha	L_t_ha	8
Ca_%_2012_1st	0		0.6316
	40		0.5895
	80		0.5170
	120		0.5660
Ca_%_2012_2nd	0		1.0558
	40		1.0305
	80		0.9727
	120		1.0265
Ca_%_2013_1st	0		1.0755
	40		1.1894
	80		1.2412
	120		1.1614
Ca_%_2013_2nd	0		1.5812
	40		1.4757
	80		1.4428
	120		1.6042
Ca_%_2014_1st	0		1.2265
	40		0.9782
	80		1.0578
	120		1.0159
Ca_%_2014_2nd	0		0.9998
	40		0.8844
	80		0.8700
	120		0.8617

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	192	192	192
d.f.	372.42	84	84	84
l.s.d.	0.03961	0.03715	0.03715	0.03715

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	48	32
l.s.d.	0.08166	0.08166	0.07429	0.08166
d.f.	453.19	453.19	84	453.19

Except when comparing means with the same level(s) of

N_kg_ha	0.07921			
d.f.	372.42			
P_kg_ha		0.07921		
d.f.		372.42		
L_t_ha				0.07921
d.f.				372.42

Table	N_kg_ha	P_kg_ha	Time	Time
	L_t_ha	L_t_ha	N_kg_ha	N_kg_ha
			P_kg_ha	L_t_ha
rep.	48	48	8	8
l.s.d.	0.07429	0.07429	0.16332	0.16332
d.f.	84	84	453.19	453.19

Except when comparing means with the same level(s) of

N_kg_ha.P_kg_ha		0.15842	
d.f.		372.42	
N_kg_ha.L_t_ha			0.15842
d.f.			372.42

Table	Time
	P_kg_ha
	L_t_ha
rep.	8
l.s.d.	0.16332
d.f.	453.19

Except when comparing means with the same level(s) of

P_kg_ha.L_t_ha	0.15842
d.f.	372.42

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate:

Ca_%_2012_1st,Ca_%_2012_2nd,Ca_%_2013_1st,Ca_%_2013_2nd,Ca_%_2014_1st,Ca_%_2014_2nd

Stratum	d.f.	s.e.	cv%
rep	1	0.01446	1.5
rep.block	6	0.03102	3.2
rep.block.Subject	84	0.07472	7.8
rep.block.Subject.Time	455	0.15558	16.2

Analysis of variance

Variate:

Mg_%_2012_1st,Mg_%_2012_2nd,Mg_%_2013_1st,Mg_%_2013_2nd,Mg_%_2014_1st,Mg_%_2014_2nd

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	0.090669	0.090669	26.86	
rep.block stratum	6	0.020254	0.003376	1.08	
rep.block.Subject stratum					
N_kg_ha	3	0.032685	0.010895	3.49	0.019
P_kg_ha	3	0.037978	0.012659	4.06	0.010
L_t_ha	3	0.018224	0.006075	1.95	0.128
N_kg_ha.P_kg_ha	9	0.023205	0.002578	0.83	0.593
N_kg_ha.L_t_ha	9	0.031684	0.003520	1.13	0.352
P_kg_ha.L_t_ha	9	0.047142	0.005238	1.68	0.107
Residual	84	0.262010	0.003119	2.76	
rep.block.Subject.Time stratum					
d.f. correction factor 0.8390					
Time	5	1.112112	0.222422	196.54	<.001
Time.N_kg_ha	15	0.035792	0.002386	2.11	0.014
Time.P_kg_ha	15	0.015132	0.001009	0.89	0.560
Time.L_t_ha	15	0.022798	0.001520	1.34	0.188
Time.N_kg_ha.P_kg_ha	45	0.041976	0.000933	0.82	0.762
Time.N_kg_ha.L_t_ha	45	0.054605	0.001213	1.07	0.360
Time.P_kg_ha.L_t_ha	45	0.050553	0.001123	0.99	0.486
Residual	455	0.514912	0.001132		
Total	767	2.411730			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 block 4 Subject 1 Time Mg_%_2013_2nd	0.1058	s.e. 0.0259
rep 2 block 1 Subject 8 Time Mg_%_2013_2nd	0.0926	s.e. 0.0259
rep 2 block 2 Subject 9 Time Mg_%_2014_1st	0.0855	s.e. 0.0259
rep 2 block 3 Subject 9 Time Mg_%_2014_1st	0.0830	s.e. 0.0259

Tables of means

Variate:

Mg_%_2012_1st, Mg_%_2012_2nd, Mg_%_2013_1st, Mg_%_2013_2nd, Mg_%_2014_1st, Mg_%_2014_2nd

Grand mean 0.3202

Time	Mg_%_2012_1st	Mg_%_2012_2nd	Mg_%_2013_1st	Mg_%_2013_2nd	Mg_%_2014_1st
	0.2446	0.3072	0.3483	0.3529	0.3508

Time	Mg_%_2014_2nd
	0.3176

N_kg_ha	0	80	160	240
	0.3105	0.3199	0.3288	0.3216

P_kg_ha	0	40	80	120
	0.3153	0.3164	0.3169	0.3324

L_t_ha	0	2	4	8
	0.3222	0.3273	0.3158	0.3156

Time	N_kg_ha	0	80	160	240
Mg_%_2012_1st		0.2467	0.2448	0.2480	0.2387
Mg_%_2012_2nd		0.3081	0.3103	0.3073	0.3031
Mg_%_2013_1st		0.3392	0.3471	0.3571	0.3499
Mg_%_2013_2nd		0.3264	0.3501	0.3667	0.3682
Mg_%_2014_1st		0.3359	0.3452	0.3668	0.3553
Mg_%_2014_2nd		0.3068	0.3219	0.3270	0.3146

Time	P_kg_ha	0	40	80	120
Mg_%_2012_1st		0.2421	0.2459	0.2385	0.2518
Mg_%_2012_2nd		0.3100	0.3031	0.3010	0.3147
Mg_%_2013_1st		0.3377	0.3482	0.3479	0.3595
Mg_%_2013_2nd		0.3433	0.3499	0.3481	0.3702
Mg_%_2014_1st		0.3421	0.3395	0.3490	0.3726
Mg_%_2014_2nd		0.3167	0.3117	0.3167	0.3253

N_kg_ha	P_kg_ha	0	40	80	120
0		0.3117	0.3069	0.3055	0.3180
80		0.3178	0.3246	0.3127	0.3246
160		0.3248	0.3206	0.3274	0.3425
240		0.3069	0.3133	0.3219	0.3445

Time	L_t_ha	0	2	4	8
Mg_%_2012_1st		0.2432	0.2509	0.2480	0.2362
Mg_%_2012_2nd		0.3022	0.3140	0.3078	0.3048
Mg_%_2013_1st		0.3575	0.3584	0.3407	0.3366
Mg_%_2013_2nd		0.3510	0.3585	0.3508	0.3511
Mg_%_2014_1st		0.3611	0.3624	0.3406	0.3391
Mg_%_2014_2nd		0.3182	0.3195	0.3071	0.3255

N_kg_ha	L_t_ha	0	2	4	8
0		0.3130	0.3135	0.3004	0.3151
80		0.3095	0.3299	0.3250	0.3152
160		0.3400	0.3400	0.3153	0.3200
240		0.3263	0.3257	0.3226	0.3120

P_kg_ha	L_t_ha	0	2	4	8

0	0.3173	0.3169	0.3134	0.3136
40	0.3098	0.3277	0.3244	0.3035
80	0.3297	0.3295	0.3062	0.3021
120	0.3320	0.3351	0.3193	0.3430

Time	N_kg_ha	P_kg_ha	0	40	80
Mg_%_2012_1st	0		0.2434	0.2467	0.2451
	80		0.2435	0.2544	0.2411
	160		0.2538	0.2451	0.2276
	240		0.2276	0.2373	0.2404
Mg_%_2012_2nd	0		0.3093	0.3083	0.2973
	80		0.3114	0.3105	0.3186
	160		0.3026	0.3012	0.3033
	240		0.3165	0.2924	0.2849
Mg_%_2013_1st	0		0.3468	0.3337	0.3411
	80		0.3412	0.3545	0.3335
	160		0.3351	0.3587	0.3673
	240		0.3276	0.3457	0.3497
Mg_%_2013_2nd	0		0.3133	0.3268	0.3219
	80		0.3507	0.3633	0.3258
	160		0.3762	0.3540	0.3630
	240		0.3328	0.3553	0.3816
Mg_%_2014_1st	0		0.3415	0.3234	0.3285
	80		0.3411	0.3379	0.3324
	160		0.3544	0.3547	0.3673
	240		0.3315	0.3418	0.3678
Mg_%_2014_2nd	0		0.3160	0.3025	0.2991
	80		0.3189	0.3269	0.3249
	160		0.3268	0.3097	0.3358
	240		0.3052	0.3075	0.3069

Time	N_kg_ha	P_kg_ha	120
Mg_%_2012_1st	0		0.2516
	80		0.2402
	160		0.2657
	240		0.2496
Mg_%_2012_2nd	0		0.3176
	80		0.3008
	160		0.3218
	240		0.3186
Mg_%_2013_1st	0		0.3351
	80		0.3591
	160		0.3674
	240		0.3765
Mg_%_2013_2nd	0		0.3436
	80		0.3607
	160		0.3735
	240		0.4032
Mg_%_2014_1st	0		0.3501
	80		0.3696
	160		0.3906
	240		0.3801
Mg_%_2014_2nd	0		0.3096
	80		0.3168
	160		0.3358
	240		0.3388

Time	N_kg_ha	L_t_ha	0	2	4
Mg_%_2012_1st	0		0.2461	0.2630	0.2291
	80		0.2294	0.2522	0.2564

	160		0.2591	0.2488	0.2599
	240		0.2383	0.2398	0.2464
Mg_%_2012_2nd	0		0.3090	0.3047	0.2990
	80		0.2894	0.3233	0.3197
	160		0.3092	0.3139	0.3130
	240		0.3013	0.3141	0.2994
Mg_%_2013_1st	0		0.3685	0.3360	0.3261
	80		0.3495	0.3608	0.3443
	160		0.3514	0.3829	0.3423
	240		0.3604	0.3541	0.3500
Mg_%_2013_2nd	0		0.3215	0.3361	0.3216
	80		0.3238	0.3474	0.3718
	160		0.3989	0.3748	0.3314
	240		0.3600	0.3755	0.3785
Mg_%_2014_1st	0		0.3350	0.3334	0.3265
	80		0.3435	0.3626	0.3436
	160		0.3896	0.3887	0.3373
	240		0.3763	0.3646	0.3549
Mg_%_2014_2nd	0		0.2981	0.3079	0.3002
	80		0.3212	0.3332	0.3142
	160		0.3318	0.3308	0.3076
	240		0.3216	0.3062	0.3063

Time	N_kg_ha	L_t_ha	8		
Mg_%_2012_1st	0		0.2486		
	80		0.2413		
	160		0.2244		
	240		0.2303		
Mg_%_2012_2nd	0		0.3199		
	80		0.3089		
	160		0.2929		
	240		0.2976		
Mg_%_2013_1st	0		0.3260		
	80		0.3337		
	160		0.3519		
	240		0.3350		
Mg_%_2013_2nd	0		0.3264		
	80		0.3574		
	160		0.3616		
	240		0.3589		
Mg_%_2014_1st	0		0.3486		
	80		0.3312		
	160		0.3514		
	240		0.3254		
Mg_%_2014_2nd	0		0.3209		
	80		0.3190		
	160		0.3379		
	240		0.3244		

Time	P_kg_ha	L_t_ha	0	2	4
Mg_%_2012_1st	0		0.2413	0.2477	0.2385
	40		0.2423	0.2549	0.2550
	80		0.2501	0.2484	0.2348
	120		0.2392	0.2528	0.2635
Mg_%_2012_2nd	0		0.3042	0.3224	0.3032
	40		0.3019	0.3007	0.3123
	80		0.2941	0.3108	0.3111
	120		0.3088	0.3220	0.3045
Mg_%_2013_1st	0		0.3508	0.3335	0.3484
	40		0.3372	0.3789	0.3469

	80	0.3778	0.3513	0.3310
	120	0.3642	0.3702	0.3364
Mg_%_2013_2nd	0	0.3422	0.3265	0.3551
	40	0.3388	0.3571	0.3737
	80	0.3599	0.3663	0.3365
	120	0.3633	0.3839	0.3380
Mg_%_2014_1st	0	0.3452	0.3584	0.3276
	40	0.3319	0.3509	0.3552
	80	0.3712	0.3789	0.3211
	120	0.3961	0.3613	0.3584
Mg_%_2014_2nd	0	0.3201	0.3127	0.3076
	40	0.3070	0.3235	0.3033
	80	0.3250	0.3216	0.3024
	120	0.3206	0.3204	0.3149

	Time	P_kg_ha	L_t_ha	8
Mg_%_2012_1st		0		0.2407
		40		0.2314
		80		0.2209
		120		0.2517
Mg_%_2012_2nd		0		0.3100
		40		0.2976
		80		0.2882
		120		0.3235
Mg_%_2013_1st		0		0.3179
		40		0.3296
		80		0.3315
		120		0.3675
Mg_%_2013_2nd		0		0.3492
		40		0.3299
		80		0.3296
		120		0.3957
Mg_%_2014_1st		0		0.3374
		40		0.3198
		80		0.3248
		120		0.3746
Mg_%_2014_2nd		0		0.3265
		40		0.3128
		80		0.3177
		120		0.3451

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	192	192	192
d.f.	381.77	84	84	84
l.s.d.	0.00853	0.01134	0.01134	0.01134

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	48	32
l.s.d.	0.01939	0.01939	0.02267	0.01939
d.f.	385.82	385.82	84	385.82

Except when comparing means with the same level(s) of

N_kg_ha	0.01705			
d.f.	381.77			
P_kg_ha		0.01705		
d.f.		381.77		
L_t_ha				0.01705

d.f.				381.77
Table	N_kg_ha L_t_ha	P_kg_ha L_t_ha	Time N_kg_ha P_kg_ha	Time N_kg_ha L_t_ha
rep.	48	48	8	8
l.s.d.	0.02267	0.02267	0.03878	0.03878
d.f.	84	84	385.82	385.82
Except when comparing means with the same level(s) of				
N_kg_ha.P_kg_ha			0.03411	
d.f.			381.77	
N_kg_ha.L_t_ha				0.03411
d.f.				381.77

Table	Time P_kg_ha L_t_ha
rep.	8
l.s.d.	0.03878
d.f.	385.82
Except when comparing means with the same level(s) of	
P_kg_ha.L_t_ha	0.03411
d.f.	381.77

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate:

Mg_%_2012_1st,Mg_%_2012_2nd,Mg_%_2013_1st,Mg_%_2013_2nd,Mg_%_2014_1st,Mg_%_2014_2nd

Stratum	d.f.	s.e.	cv%
rep	1	0.01537	4.8
rep.block	6	0.00593	1.9
rep.block.Subject	84	0.02280	7.1
rep.block.Subject.Time	455	0.03364	10.5

Analysis of variance

Variate:

N_%_2012_1st,N_%_2012_2nd,N_%_2013_1st,N_%_2013_2nd,N_%_2014_1st,N_%_2014_2nd

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	0.15149	0.15149	0.37	
rep.block stratum	6	2.46926	0.41154	3.33	
rep.block.Subject stratum					
N_kg_ha	3	8.60109	2.86703	23.19	<.001
P_kg_ha	3	0.51109	0.17036	1.38	0.255
L_t_ha	3	1.92206	0.64069	5.18	0.002
N_kg_ha.P_kg_ha	9	1.72817	0.19202	1.55	0.143
N_kg_ha.L_t_ha	9	0.88506	0.09834	0.80	0.622
P_kg_ha.L_t_ha	9	0.63882	0.07098	0.57	0.815
Residual	84	10.38709	0.12366	1.38	

rep.block.Subject.Time stratum					
d.f. correction factor 0.7915					
Time	5	353.31919	70.66384	788.70	<.001
Time.N_kg_ha	15	8.28064	0.55204	6.16	<.001
Time.P_kg_ha	15	1.65303	0.11020	1.23	0.261
Time.L_t_ha	15	1.61881	0.10792	1.20	0.278
Time.N_kg_ha.P_kg_ha	45	5.32911	0.11842	1.32	0.109
Time.N_kg_ha.L_t_ha	45	5.24855	0.11663	1.30	0.122
Time.P_kg_ha.L_t_ha	45	2.78456	0.06188	0.69	0.911
Residual	455	40.76570	0.08959		
Total	767	446.29373			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 block 3 Subject 10	0.308	s.e. 0.116
rep 1 block 1 Subject 13 Time N_%_2012_1st	0.732	s.e. 0.230
rep 1 block 3 Subject 8 Time N_%_2012_1st	0.727	s.e. 0.230
rep 1 block 4 Subject 9 Time N_%_2012_1st	-0.748	s.e. 0.230
rep 2 block 1 Subject 3 Time N_%_2012_1st	-0.708	s.e. 0.230

Tables of means

Variate:

N_%_2012_1st,N_%_2012_2nd,N_%_2013_1st,N_%_2013_2nd,N_%_2014_1st,N_%_2014_2nd

Grand mean 3.057

Time	N_%_2012_1st	N_%_2012_2nd	N_%_2013_1st	N_%_2013_2nd	N_%_2014_1st
	4.018	2.270	3.740	2.190	3.066

Time	N_%_2014_2nd
	3.061

N_kg_ha	0	80	160	240
	2.903	3.015	3.144	3.166

P_kg_ha	0	40	80	120
	3.033	3.031	3.078	3.088

L_t_ha	0	2	4	8
	3.111	3.088	2.979	3.050

Time	N_kg_ha	0	80	160	240
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N_%_2012_1st	4.019	4.064	3.956	4.033
N_%_2012_2nd	2.178	2.270	2.292	2.340
N_%_2013_1st	3.435	3.524	3.979	4.021
N_%_2013_2nd	2.143	2.170	2.189	2.257
N_%_2014_1st	2.733	3.015	3.297	3.218
N_%_2014_2nd	2.913	3.050	3.152	3.127

Time	P_kg_ha	0	40	80	120
N_%_2012_1st		3.998	4.008	4.052	4.012
N_%_2012_2nd		2.244	2.277	2.284	2.275
N_%_2013_1st		3.807	3.656	3.731	3.763
N_%_2013_2nd		2.212	2.191	2.209	2.146
N_%_2014_1st		2.949	3.028	3.074	3.213
N_%_2014_2nd		2.984	3.025	3.115	3.118

N_kg_ha	P_kg_ha	0	40	80	120
0		2.894	2.748	2.969	3.003
80		2.968	3.060	3.026	3.008
160		3.145	3.126	3.136	3.170
240		3.123	3.190	3.180	3.171

Time	L_t_ha	0	2	4	8
N_%_2012_1st		4.052	4.056	3.903	4.061
N_%_2012_2nd		2.379	2.247	2.243	2.211
N_%_2013_1st		3.811	3.855	3.555	3.737
N_%_2013_2nd		2.182	2.178	2.189	2.209
N_%_2014_1st		3.143	3.121	2.983	3.015
N_%_2014_2nd		3.101	3.074	3.003	3.064

N_kg_ha	L_t_ha	0	2	4	8
0		2.963	2.945	2.784	2.922
80		3.009	3.014	2.995	3.043
160		3.240	3.201	3.027	3.109
240		3.234	3.194	3.112	3.125

P_kg_ha	L_t_ha	0	2	4	8
0		3.097	3.084	2.959	2.991
40		3.067	3.069	2.984	3.003
80		3.106	3.143	2.959	3.103
120		3.176	3.059	3.016	3.101

Time	N_kg_ha	P_kg_ha	0	40	80
N_%_2012_1st	0		3.975	3.622	4.282
	80		3.947	4.290	4.008
	160		3.916	4.123	3.856
	240		4.155	3.995	4.064
N_%_2012_2nd	0		2.178	2.235	2.146
	80		2.208	2.217	2.210
	160		2.349	2.317	2.287
	240		2.242	2.339	2.494
N_%_2013_1st	0		3.570	3.183	3.370
	80		3.620	3.597	3.590
	160		4.085	3.784	4.014
	240		3.954	4.062	3.952
N_%_2013_2nd	0		2.094	2.185	2.169
	80		2.221	2.128	2.262
	160		2.226	2.225	2.139
	240		2.307	2.227	2.267
N_%_2014_1st	0		2.678	2.507	2.830
	80		2.868	3.026	3.014

	160	3.234	3.260	3.231
	240	3.016	3.318	3.219
N_%_2014_2nd	0	2.871	2.755	3.016
	80	2.941	3.100	3.073
	160	3.062	3.045	3.288
	240	3.063	3.201	3.082

Time	N_kg_ha	P_kg_ha	120			
N_%_2012_1st	0		4.196			
	80		4.009			
	160		3.928			
	240		3.917			
N_%_2012_2nd	0		2.153			
	80		2.445			
	160		2.217			
	240		2.285			
N_%_2013_1st	0		3.617			
	80		3.288			
	160		4.033			
	240		4.115			
N_%_2013_2nd	0		2.122			
	80		2.070			
	160		2.163			
	240		2.229			
N_%_2014_1st	0		2.916			
	80		3.153			
	160		3.464			
	240		3.318			
N_%_2014_2nd	0		3.012			
	80		3.084			
	160		3.215			
	240		3.162			

Time	N_kg_ha	L_t_ha	0	2	4	8
N_%_2012_1st	0		4.113	4.117	3.789	4.056
	80		3.974	3.968	4.057	4.256
	160		4.213	4.047	3.744	3.820
	240		3.907	4.091	4.021	4.111
N_%_2012_2nd	0		2.241	2.155	2.107	2.209
	80		2.337	2.176	2.312	2.255
	160		2.433	2.350	2.121	2.266
	240		2.505	2.309	2.432	2.114
N_%_2013_1st	0		3.263	3.568	3.274	3.634
	80		3.477	3.600	3.460	3.558
	160		4.240	4.068	3.809	3.799
	240		4.264	4.182	3.679	3.957
N_%_2013_2nd	0		2.189	2.164	2.177	2.040
	80		2.059	2.230	2.164	2.229
	160		2.145	2.111	2.207	2.292
	240		2.336	2.209	2.208	2.275
N_%_2014_1st	0		2.928	2.770	2.484	2.750
	80		3.141	3.041	2.986	2.892
	160		3.305	3.422	3.195	3.267
	240		3.199	3.251	3.268	3.153
N_%_2014_2nd	0		3.042	2.898	2.872	2.841
	80		3.069	3.067	2.991	3.071
	160		3.105	3.208	3.086	3.210
	240		3.190	3.120	3.063	3.136

Time	P_kg_ha	L_t_ha	0	2	4	8
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N_%_2012_1st	0	3.961	4.129	3.892	4.011
	40	4.064	3.957	3.846	4.163
	80	4.132	4.185	3.860	4.033
	120	4.049	3.952	4.013	4.036
N_%_2012_2nd	0	2.390	2.232	2.223	2.132
	40	2.304	2.291	2.333	2.180
	80	2.383	2.265	2.190	2.300
	120	2.439	2.201	2.227	2.233
N_%_2013_1st	0	3.760	3.933	3.672	3.865
	40	3.613	3.778	3.598	3.636
	80	3.862	3.920	3.386	3.759
	120	4.009	3.788	3.566	3.689
N_%_2013_2nd	0	2.233	2.165	2.209	2.241
	40	2.197	2.242	2.137	2.190
	80	2.193	2.183	2.250	2.211
	120	2.106	2.122	2.161	2.194
N_%_2014_1st	0	3.159	3.034	2.795	2.808
	40	3.134	3.145	2.943	2.890
	80	2.992	3.092	3.071	3.139
	120	3.288	3.214	3.124	3.225
N_%_2014_2nd	0	3.076	3.009	2.963	2.888
	40	3.091	2.999	3.049	2.961
	80	3.072	3.212	2.998	3.177
	120	3.166	3.075	3.001	3.232

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	192	192	192
d.f.	360.14	84	84	84
l.s.d.	0.0766	0.0714	0.0714	0.0714

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	48	32
l.s.d.	0.1580	0.1580	0.1427	0.1580
d.f.	442.01	442.01	84	442.01

Except when comparing means with the same level(s) of

N_kg_ha	0.1533			
d.f.	360.14			
P_kg_ha		0.1533		
d.f.		360.14		
L_t_ha			0.1533	
d.f.			360.14	

Table	N_kg_ha	P_kg_ha	Time	Time
	L_t_ha	L_t_ha	N_kg_ha	N_kg_ha
			P_kg_ha	L_t_ha
rep.	48	48	8	8
l.s.d.	0.1427	0.1427	0.3160	0.3160
d.f.	84	84	442.01	442.01

Except when comparing means with the same level(s) of

N_kg_ha.P_kg_ha	0.3066			
d.f.	360.14			
N_kg_ha.L_t_ha			0.3066	
d.f.			360.14	

Table	Time
	P_kg_ha

	L_t_ha
rep.	8
l.s.d.	0.3160
d.f.	442.01
Except when comparing means with the same level(s) of	
P_kg_ha.L_t_ha	0.3066
d.f.	360.14

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate:

N_%_2012_1st,N_%_2012_2nd,N_%_2013_1st,N_%_2013_2nd,N_%_2014_1st,N_%_2014_2nd

Stratum	d.f.	s.e.	cv%
rep	1	0.0199	0.6
rep.block	6	0.0655	2.1
rep.block.Subject	84	0.1436	4.7
rep.block.Subject.Time	455	0.2993	9.8

Analysis of variance

Variate:

P_%_2012_1st,P_%_2012_2nd,P_%_2013_1st,P_%_2013_2nd,P_%_2014_1st,P_%_2014_2nd

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	0.023862	0.023862	3.94	
rep.block stratum	6	0.036356	0.006059	4.58	
rep.block.Subject stratum					
N_kg_ha	3	0.038752	0.012917	9.76	<.001
P_kg_ha	3	0.027486	0.009162	6.92	<.001
L_t_ha	3	0.021462	0.007154	5.40	0.002
N_kg_ha.P_kg_ha	9	0.031647	0.003516	2.66	0.009
N_kg_ha.L_t_ha	9	0.021153	0.002350	1.78	0.085
P_kg_ha.L_t_ha	9	0.007418	0.000824	0.62	0.775
Residual	84	0.111183	0.001324	0.71	
rep.block.Subject.Time stratum					
d.f. correction factor 0.7325					
Time	5	5.770822	1.154164	617.14	<.001
Time.N_kg_ha	15	0.196625	0.013108	7.01	<.001
Time.P_kg_ha	15	0.033184	0.002212	1.18	0.298
Time.L_t_ha	15	0.054487	0.003632	1.94	0.034
Time.N_kg_ha.P_kg_ha	45	0.069868	0.001553	0.83	0.736
Time.N_kg_ha.L_t_ha	45	0.063363	0.001408	0.75	0.837
Time.P_kg_ha.L_t_ha	45	0.045828	0.001018	0.54	0.982
Residual	455	0.850934	0.001870		
Total	767	7.404432			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 block 1	0.0146	s.e. 0.0069
rep 1 block 1 Subject 8 Time P_%_2012_1st	0.1111	s.e. 0.0333
rep 1 block 4 Subject 9 Time P_%_2014_1st	0.1093	s.e. 0.0333
rep 2 block 3 Subject 16 Time P_%_2013_1st	0.1352	s.e. 0.0333

Tables of means

Variate:

P_%_2012_1st,P_%_2012_2nd,P_%_2013_1st,P_%_2013_2nd,P_%_2014_1st,P_%_2014_2nd

Grand mean 0.3250

Time	P_%_2012_1st	P_%_2012_2nd	P_%_2013_1st	P_%_2013_2nd	P_%_2014_1st
	0.3976	0.2276	0.4567	0.2169	0.3510

Time	P_%_2014_2nd
	0.3004

N_kg_ha	0	80	160	240
	0.3363	0.3242	0.3230	0.3166

P_kg_ha	0	40	80	120
	0.3149	0.3268	0.3304	0.3280

L_t_ha	0	2	4	8
	0.3222	0.3206	0.3234	0.3340

Time	N_kg_ha	0	80	160	240
P_%_2012_1st		0.3984	0.4028	0.3944	0.3949
P_%_2012_2nd		0.2204	0.2293	0.2300	0.2307
P_%_2013_1st		0.5239	0.4538	0.4371	0.4121
P_%_2013_2nd		0.2242	0.2126	0.2175	0.2133
P_%_2014_1st		0.3434	0.3514	0.3530	0.3562
P_%_2014_2nd		0.3073	0.2954	0.3064	0.2925

Time	P_kg_ha	0	40	80	120
P_%_2012_1st		0.3915	0.4119	0.3963	0.3909
P_%_2012_2nd		0.2196	0.2328	0.2316	0.2264
P_%_2013_1st		0.4466	0.4551	0.4577	0.4675
P_%_2013_2nd		0.2116	0.2189	0.2232	0.2138
P_%_2014_1st		0.3388	0.3401	0.3576	0.3675
P_%_2014_2nd		0.2815	0.3021	0.3162	0.3017

N_kg_ha	P_kg_ha	0	40	80	120
0		0.3197	0.3344	0.3452	0.3458
80		0.3104	0.3188	0.3313	0.3364
160		0.3134	0.3304	0.3326	0.3158

240		0.3162	0.3237	0.3126	0.3139
Time	L_t_ha	0	2	4	8
P_%_2012_1st		0.3965	0.4112	0.3812	0.4016
P_%_2012_2nd		0.2346	0.2234	0.2231	0.2294
P_%_2013_1st		0.4522	0.4426	0.4533	0.4789
P_%_2013_2nd		0.2055	0.2066	0.2222	0.2332
P_%_2014_1st		0.3527	0.3511	0.3556	0.3446
P_%_2014_2nd		0.2917	0.2885	0.3047	0.3166
N_kg_ha	L_t_ha	0	2	4	8
0		0.3386	0.3261	0.3373	0.3430
80		0.3292	0.3241	0.3153	0.3283
160		0.3159	0.3159	0.3280	0.3323
240		0.3051	0.3161	0.3128	0.3325
P_kg_ha	L_t_ha	0	2	4	8
0		0.3131	0.3097	0.3153	0.3216
40		0.3241	0.3218	0.3217	0.3397
80		0.3218	0.3295	0.3336	0.3369
120		0.3298	0.3212	0.3228	0.3380
Time	N_kg_ha	P_kg_ha	0	40	80
P_%_2012_1st	0		0.3858	0.3818	0.4327
	80		0.3949	0.4281	0.3937
	160		0.3833	0.4236	0.3881
	240		0.4018	0.4140	0.3707
P_%_2012_2nd	0		0.2150	0.2358	0.2154
	80		0.2219	0.2220	0.2317
	160		0.2211	0.2367	0.2331
	240		0.2203	0.2368	0.2461
P_%_2013_1st	0		0.4993	0.5223	0.5235
	80		0.4220	0.4263	0.4736
	160		0.4454	0.4424	0.4459
	240		0.4197	0.4294	0.3879
P_%_2013_2nd	0		0.2116	0.2336	0.2239
	80		0.2083	0.2101	0.2277
	160		0.2100	0.2216	0.2281
	240		0.2167	0.2104	0.2132
P_%_2014_1st	0		0.3258	0.3254	0.3534
	80		0.3407	0.3284	0.3577
	160		0.3385	0.3537	0.3596
	240		0.3502	0.3528	0.3597
P_%_2014_2nd	0		0.2809	0.3074	0.3222
	80		0.2746	0.2980	0.3034
	160		0.2822	0.3042	0.3410
	240		0.2884	0.2989	0.2980
Time	N_kg_ha	P_kg_ha	120		
P_%_2012_1st	0		0.3934		
	80		0.3944		
	160		0.3825		
	240		0.3932		
P_%_2012_2nd	0		0.2155		
	80		0.2418		
	160		0.2290		
	240		0.2195		
P_%_2013_1st	0		0.5506		
	80		0.4934		
	160		0.4146		

	240	0.4116
P_%_2013_2nd	0	0.2279
	80	0.2044
	160	0.2101
	240	0.2127
P_%_2014_1st	0	0.3689
	80	0.3787
	160	0.3603
	240	0.3620
P_%_2014_2nd	0	0.3186
	80	0.3056
	160	0.2980
	240	0.2847

Time	N_kg_ha	L_t_ha	0	2	4	8
P_%_2012_1st	0		0.3989	0.3892	0.3960	0.4096
	80		0.4105	0.4355	0.3862	0.3790
	160		0.3911	0.4154	0.3613	0.4097
	240		0.3856	0.4048	0.3815	0.4080
P_%_2012_2nd	0		0.2306	0.2095	0.2172	0.2244
	80		0.2361	0.2183	0.2313	0.2317
	160		0.2325	0.2398	0.2112	0.2363
	240		0.2391	0.2259	0.2326	0.2252
P_%_2013_1st	0		0.5239	0.5038	0.5251	0.5427
	80		0.4584	0.4460	0.4274	0.4835
	160		0.4297	0.4182	0.4630	0.4374
	240		0.3968	0.4023	0.3977	0.4517
P_%_2013_2nd	0		0.2113	0.2148	0.2335	0.2374
	80		0.2027	0.2135	0.2116	0.2226
	160		0.2051	0.1963	0.2331	0.2353
	240		0.2030	0.2020	0.2107	0.2372
P_%_2014_1st	0		0.3623	0.3530	0.3325	0.3257
	80		0.3698	0.3453	0.3440	0.3464
	160		0.3474	0.3384	0.3789	0.3473
	240		0.3311	0.3678	0.3669	0.3589
P_%_2014_2nd	0		0.3047	0.2865	0.3195	0.3184
	80		0.2975	0.2861	0.2913	0.3066
	160		0.2898	0.2875	0.3205	0.3276
	240		0.2748	0.2937	0.2875	0.3140

Time	P_kg_ha	L_t_ha	0	2	4	8
P_%_2012_1st	0		0.3666	0.4145	0.3810	0.4038
	40		0.4147	0.4087	0.3922	0.4320
	80		0.4070	0.4186	0.3723	0.3874
	120		0.3978	0.4032	0.3794	0.3831
P_%_2012_2nd	0		0.2295	0.2109	0.2227	0.2152
	40		0.2404	0.2282	0.2276	0.2351
	80		0.2355	0.2307	0.2264	0.2337
	120		0.2328	0.2236	0.2157	0.2336
P_%_2013_1st	0		0.4379	0.4224	0.4569	0.4691
	40		0.4449	0.4441	0.4480	0.4834
	80		0.4506	0.4555	0.4601	0.4647
	120		0.4754	0.4483	0.4483	0.4982
P_%_2013_2nd	0		0.2070	0.1931	0.2125	0.2339
	40		0.2002	0.2212	0.2183	0.2359
	80		0.2092	0.2105	0.2360	0.2372
	120		0.2057	0.2017	0.2221	0.2255
P_%_2014_1st	0		0.3578	0.3446	0.3328	0.3200
	40		0.3410	0.3465	0.3344	0.3384
	80		0.3395	0.3548	0.3793	0.3568

	120	0.3724	0.3587	0.3758	0.3632
P_%_2014_2nd	0	0.2799	0.2729	0.2861	0.2873
	40	0.3032	0.2824	0.3096	0.3133
	80	0.2890	0.3066	0.3275	0.3415
	120	0.2948	0.2920	0.2956	0.3245

Least significant differences of means (5% level)

Table	Time	N_kg_ha	P_kg_ha	L_t_ha
rep.	128	192	192	192
d.f.	333.28	84	84	84
l.s.d.	0.01122	0.00738	0.00738	0.00738

Table	Time	Time	N_kg_ha	Time
	N_kg_ha	P_kg_ha	P_kg_ha	L_t_ha
rep.	32	32	48	32
l.s.d.	0.02188	0.02188	0.01477	0.02188
d.f.	402.33	402.33	84	402.33

Except when comparing means with the same level(s) of

N_kg_ha	0.02245			
d.f.	333.28			
P_kg_ha		0.02245		
d.f.		333.28		
L_t_ha				0.02245
d.f.				333.28

Table	N_kg_ha	P_kg_ha	Time	Time
	L_t_ha	L_t_ha	N_kg_ha	N_kg_ha
			P_kg_ha	L_t_ha
rep.	48	48	8	8
l.s.d.	0.01477	0.01477	0.04376	0.04376
d.f.	84	84	402.33	402.33

Except when comparing means with the same level(s) of

N_kg_ha.P_kg_ha			0.04489	
d.f.			333.28	
N_kg_ha.L_t_ha				0.04489
d.f.				333.28

Table	Time
	P_kg_ha
	L_t_ha
rep.	8
l.s.d.	0.04376
d.f.	402.33
Except when comparing means with the same level(s) of	
P_kg_ha.L_t_ha	0.04489
d.f.	333.28

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate:

P_%_2012_1st,P_%_2012_2nd,P_%_2013_1st,P_%_2013_2nd,P_%_2014_1st,P_%_2014_2nd

Stratum	d.f.	s.e.	cv%
rep	1	0.00788	2.4
rep.block	6	0.00794	2.4
rep.block.Subject	84	0.01485	4.6
rep.block.Subject.Time	455	0.04325	13.3

Appendix 3.9: Chapter 3 (N x P x L) root statistical analysis

Analysis of variance

Variate: N_%_root

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	0.14521	0.14521	2.63	
rep.block stratum	6	0.33072	0.05512	3.67	
rep.block.*Units* stratum					
N_kg_ha	3	0.26223	0.08741	5.82	0.001
P_kg_ha	3	0.08062	0.02687	1.79	0.155
L_t_ha	3	0.02827	0.00942	0.63	0.599
N_kg_ha.P_kg_ha	9	0.08336	0.00926	0.62	0.780
N_kg_ha.L_t_ha	9	0.14932	0.01659	1.10	0.369
P_kg_ha.L_t_ha	9	0.10222	0.01136	0.76	0.657
Residual	84	1.26148	0.01502		
Total	127	2.44342			

Message: the following units have large residuals.

rep 1 block 1 *units* 1	0.276	s.e. 0.099
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Tables of means

Variate: N_%_root

Grand mean 0.995

N_kg_ha	0	80	160	240	
	0.933	0.978	1.015	1.055	
P_kg_ha	0	40	80	120	
	1.003	0.954	1.023	1.001	
L_t_ha	0	2	4	8	
	0.999	0.999	0.971	1.012	
N_kg_ha P_kg_ha	0	40	80	120	

0		0.952	0.873	1.000	0.906
80		0.961	0.964	1.012	0.976
160		0.995	0.991	1.035	1.038
240		1.104	0.989	1.044	1.085
N_kg_ha	L_t_ha	0	2	4	8
0		0.932	1.007	0.869	0.924
80		0.976	0.981	0.999	0.956
160		1.015	1.000	0.960	1.085
240		1.072	1.008	1.058	1.084
P_kg_ha	L_t_ha	0	2	4	8
0		0.993	1.068	0.972	0.980
40		0.946	0.947	0.933	0.992
80		1.042	0.975	1.039	1.035
120		1.016	1.006	0.942	1.042

Least significant differences of means (5% level)

Table	N_kg_ha	P_kg_ha	L_t_ha	N_kg_ha P_kg_ha
rep.	32	32	32	8
d.f.	84	84	84	84
l.s.d.	0.0609	0.0609	0.0609	0.1218

Table	N_kg_ha L_t_ha	P_kg_ha L_t_ha
rep.	8	8
d.f.	84	84
l.s.d.	0.1218	0.1218

Stratum standard errors and coefficients of variation

Variate: N_%_root

Stratum	d.f.	s.e.	cv%
rep	1	0.0476	4.8
rep.block	6	0.0587	5.9
rep.block.*Units*	84	0.1225	12.3

Fisher's protected least significant difference test

N_kg_ha

	Mean	
0	0.9328	a
80	0.9783	ab
160	1.0150	bc
240	1.0554	c

Analysis of variance

Variate: Ca_%_root

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	0.0001071	0.0001071	0.14	
rep.block stratum	6	0.0046966	0.0007828	1.39	
rep.block.*Units* stratum					
N_kg_ha	3	0.0007846	0.0002615	0.47	0.707
P_kg_ha	3	0.0010603	0.0003534	0.63	0.598
L_t_ha	3	0.0100747	0.0033582	5.97	<.001
N_kg_ha.P_kg_ha	9	0.0031250	0.0003472	0.62	0.779
N_kg_ha.L_t_ha	9	0.0047204	0.0005245	0.93	0.501
P_kg_ha.L_t_ha	9	0.0049302	0.0005478	0.97	0.467
Residual	84	0.0472170	0.0005621		
Total	127	0.0767158			

Message: the following units have large residuals.

rep 1 block 3 *units* 11	-0.0726	s.e.	0.0192
rep 2 block 3 *units* 5	0.1003	s.e.	0.0192

Tables of means

Variate: Ca_%_root

Grand mean 0.2009

N_kg_ha	0	80	160	240	
	0.2029	0.2015	0.2024	0.1967	
P_kg_ha	0	40	80	120	
	0.1985	0.2057	0.2003	0.1989	
L_t_ha	0	2	4	8	
	0.1916	0.1930	0.2066	0.2124	
N_kg_ha P_kg_ha	0	40	80	120	
0	0.2012	0.2020	0.2099	0.1985	
80	0.2016	0.2046	0.2017	0.1982	
160	0.2017	0.2023	0.1995	0.2063	
240	0.1896	0.2140	0.1902	0.1928	
N_kg_ha L_t_ha	0	2	4	8	
0	0.1865	0.2060	0.1981	0.2210	
80	0.1980	0.1880	0.2059	0.2141	
160	0.1991	0.1914	0.2124	0.2069	
240	0.1827	0.1864	0.2099	0.2077	
P_kg_ha L_t_ha	0	2	4	8	
0	0.1971	0.1896	0.1941	0.2134	
40	0.1941	0.1912	0.2159	0.2217	
80	0.1871	0.2040	0.2103	0.1999	

120 0.1879 0.1871 0.2060 0.2147

Least significant differences of means (5% level)

Table	N_kg_ha	P_kg_ha	L_t_ha	N_kg_ha P_kg_ha
rep.	32	32	32	8
d.f.	84	84	84	84
l.s.d.	0.01179	0.01179	0.01179	0.02357

Table	N_kg_ha L_t_ha	P_kg_ha L_t_ha
rep.	8	8
d.f.	84	84
l.s.d.	0.02357	0.02357

Stratum standard errors and coefficients of variation

Variate: Ca_%_root

Stratum	d.f.	s.e.	cv%
rep	1	0.00129	0.6
rep.block	6	0.00699	3.5
rep.block.*Units*	84	0.02371	11.8

Fisher's protected least significant difference test

N_kg_ha

Warning 4, code UF 2, statement 159 in procedure AMCOMPARISON

Fisher's protected LSD is not calculated as variance ratio for N_kg_ha is not significant.

Analysis of variance

Variate: Mg_%root

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	0.0000971	0.0000971	0.17	
rep.block stratum	6	0.0033872	0.0005645	4.10	
rep.block.*Units* stratum					
N_kg_ha	3	0.0002391	0.0000797	0.58	0.631
P_kg_ha	3	0.0000733	0.0000244	0.18	0.911
L_t_ha	3	0.0000883	0.0000294	0.21	0.887
N_kg_ha.P_kg_ha	9	0.0012427	0.0001381	1.00	0.445
N_kg_ha.L_t_ha	9	0.0009933	0.0001104	0.80	0.617
P_kg_ha.L_t_ha	9	0.0018949	0.0002105	1.53	0.152
Residual	84	0.0115776	0.0001378		
Total	127	0.0195935			

Message: the following units have large residuals.

rep 1 block 3 *units* 1	0.0279	s.e.	0.0095
rep 2 block 3 *units* 5	0.0256	s.e.	0.0095

Tables of means

Variate: Mg_%root

Grand mean 0.1275

N_kg_ha	0	80	160	240
	0.1254	0.1290	0.1283	0.1274
P_kg_ha	0	40	80	120
	0.1285	0.1268	0.1281	0.1268
L_t_ha	0	2	4	8
	0.1266	0.1269	0.1278	0.1287
N_kg_ha P_kg_ha	0	40	80	120
0	0.1227	0.1257	0.1312	0.1219
80	0.1344	0.1278	0.1242	0.1298
160	0.1244	0.1281	0.1313	0.1294
240	0.1323	0.1257	0.1256	0.1261
N_kg_ha L_t_ha	0	2	4	8
0	0.1255	0.1272	0.1205	0.1284
80	0.1253	0.1268	0.1351	0.1290
160	0.1260	0.1302	0.1264	0.1305
240	0.1298	0.1234	0.1294	0.1270
P_kg_ha L_t_ha	0	2	4	8
0	0.1256	0.1261	0.1267	0.1354
40	0.1273	0.1230	0.1287	0.1281
80	0.1304	0.1355	0.1244	0.1221

120

0.1233

0.1230

0.1315

0.1294

Least significant differences of means (5% level)

Table	N_kg_ha	P_kg_ha	L_t_ha	N_kg_ha P_kg_ha
rep.	32	32	32	8
d.f.	84	84	84	84
l.s.d.	0.00584	0.00584	0.00584	0.01167

Table	N_kg_ha L_t_ha	P_kg_ha L_t_ha
rep.	8	8
d.f.	84	84
l.s.d.	0.01167	0.01167

Stratum standard errors and coefficients of variation

Variate: Mg_%root

Stratum	d.f.	s.e.	cv%
rep	1	0.00123	1.0
rep.block	6	0.00594	4.7
rep.block.*Units*	84	0.01174	9.2

Fisher's protected least significant difference test

N_kg_ha

Warning 5, code UF 2, statement 159 in procedure AMCOMPARISON

Fisher's protected LSD is not calculated as variance ratio for N_kg_ha is not significant.

Analysis of variance

Variate: P_%root

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	1	0.0003999	0.0003999	0.27	
rep.block stratum	6	0.0089021	0.0014837	3.20	
rep.block.*Units* stratum					
N_kg_ha	3	0.0010678	0.0003559	0.77	0.515
P_kg_ha	3	0.0044517	0.0014839	3.20	0.027
L_t_ha	3	0.0063920	0.0021307	4.60	0.005
N_kg_ha.P_kg_ha	9	0.0044354	0.0004928	1.06	0.398
N_kg_ha.L_t_ha	9	0.0058045	0.0006449	1.39	0.205
P_kg_ha.L_t_ha	9	0.0044028	0.0004892	1.06	0.404
Residual	84	0.0389162	0.0004633		
Total	127	0.0747724			

Message: the following units have large residuals.

rep 1 block 1 *units* 1	0.0465	s.e.	0.0174
rep 1 block 1 *units* 3	0.0569	s.e.	0.0174
rep 1 block 4 *units* 8	0.0468	s.e.	0.0174
rep 2 block 2 *units* 2	-0.0496	s.e.	0.0174

Tables of means

Variate: P_%root

Grand mean 0.2204

N_kg_ha	0	80	160	240
	0.2253	0.2185	0.2196	0.2180
P_kg_ha	0	40	80	120
	0.2152	0.2160	0.2300	0.2203
L_t_ha	0	2	4	8
	0.2147	0.2149	0.2197	0.2321
N_kg_ha P_kg_ha	0	40	80	120
0	0.2255	0.2174	0.2414	0.2166
80	0.2032	0.2192	0.2273	0.2244
160	0.2115	0.2177	0.2221	0.2273
240	0.2205	0.2095	0.2293	0.2127
N_kg_ha L_t_ha	0	2	4	8
0	0.2164	0.2324	0.2207	0.2316
80	0.2149	0.2144	0.2240	0.2209
160	0.2205	0.2089	0.2173	0.2319
240	0.2070	0.2041	0.2169	0.2441
P_kg_ha L_t_ha	0	2	4	8
0	0.2132	0.2200	0.2072	0.2205

40	0.2137	0.2099	0.2164	0.2239
80	0.2241	0.2167	0.2380	0.2412
120	0.2077	0.2132	0.2172	0.2428

Least significant differences of means (5% level)

Table	N_kg_ha	P_kg_ha	L_t_ha	N_kg_ha P_kg_ha
rep.	32	32	32	8
d.f.	84	84	84	84
l.s.d.	0.01070	0.01070	0.01070	0.02140

Table	N_kg_ha L_t_ha	P_kg_ha L_t_ha
rep.	8	8
d.f.	84	84
l.s.d.	0.02140	0.02140

Stratum standard errors and coefficients of variation

Variate: P_%root

Stratum	d.f.	s.e.	cv%
rep	1	0.00250	1.1
rep.block	6	0.00963	4.4
rep.block.*Units*	84	0.02152	9.8

Fisher's protected least significant difference test

N_kg_ha

Warning 11, code UF 2, statement 159 in procedure AMCOMPARISON

Fisher's protected LSD is not calculated as variance ratio for N_kg_ha is not significant.

Appendix 4.1: Chapter 4 (N x K trial) yield statistical analysis

Analysis of variance

Variate: %2012_weight_kg,%2013_weight_kg,%2014_weight_kg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	5396.19	2698.09	20.01	
rep.Subject stratum					
Nfert	3	5095.18	1698.39	12.59	<.001
Kfert	4	483.92	120.98	0.90	0.475
Nfert.Kfert	12	1896.04	158.00	1.17	0.337
Residual	38	5124.29	134.85	2.43	

rep.Subject.Time stratum					
d.f. correction factor 0.7401					
Time	2	3259.63	1629.81	29.32	<.001
Time.Nfert	6	490.50	81.75	1.47	0.218
Time.Kfert	8	373.80	46.72	0.84	0.542
Time.Nfert.Kfert	24	1192.70	49.70	0.89	0.586
Residual	80	4446.64	55.58		
Total	179	27758.88			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 3 Subject 14 -12.95 s.e. 5.34

Tables of means

Variate: %2012_weight_kg,%2013_weight_kg,%2014_weight_kg

Grand mean 40.93

Time	%2012_weight_kg	%2013_weight_kg	%2014_weight_kg			
	35.16	42.31	45.31			
Nfert	N1	N2	N3	N4		
	33.64	39.10	42.74	48.24		
Kfert	K1	K2	K3	K4	K5	
	39.63	38.61	41.35	41.78	43.27	
Time	Nfert	N1	N2	N3	N4	
%2012_weight_kg		30.59	32.76	37.93	39.36	
%2013_weight_kg		32.91	40.17	43.70	52.48	
%2014_weight_kg		37.40	44.36	46.59	52.87	
Time	Kfert	K1	K2	K3	K4	K5
%2012_weight_kg		36.41	33.87	34.90	36.00	34.63
%2013_weight_kg		39.82	40.31	43.34	41.59	46.50
%2014_weight_kg		42.67	41.65	45.80	47.74	48.67
Nfert	Kfert	K1	K2	K3	K4	K5
N1		31.04	31.51	32.33	39.17	34.12
N2		38.28	33.11	37.41	41.31	45.37
N3		47.34	38.29	46.93	38.08	43.06
N4		41.88	51.51	48.72	48.55	50.52
Time	Nfert	Kfert	K1	K2	K3	K4
%2012_weight_kg	N1		29.15	30.33	32.18	33.40
	N2		36.54	30.01	29.23	33.76
	N3		40.14	34.79	36.40	37.73
	N4		39.80	40.33	41.80	39.11

%2013_weight_kg	N1	30.36	30.33	28.24	38.73
	N2	35.21	32.57	40.86	44.82
	N3	52.44	39.87	52.82	31.29
	N4	41.28	58.46	51.43	51.53
%2014_weight_kg	N1	33.61	33.87	36.58	45.38
	N2	43.09	36.75	42.15	45.34
	N3	49.43	40.21	51.57	45.21
	N4	44.55	55.75	52.92	55.01
Time %2012_weight_kg	Nfert		Kfert	K5	
	N1			27.90	
	N2			34.27	
	N3			40.58	
%2013_weight_kg	N1			36.90	
	N2			47.37	
	N3			42.06	
	N4			59.68	
%2014_weight_kg	N1			37.56	
	N2			54.48	
	N3			46.54	
	N4			56.11	

Least significant differences of means (5% level)

Table	Time	Nfert	Kfert	Time Nfert
rep.	60	45	36	15
l.s.d.	2.865	4.956	5.541	6.918
d.f.	59.21	38	38	88.06
Except when comparing means with the same level(s) of Nfert				5.731
d.f.				59.21

Table	Time Kfert	Nfert Kfert	Time Nfert Kfert
rep.	12	9	3
l.s.d.	7.734	11.082	15.468
d.f.	88.06	38	88.06
Except when comparing means with the same level(s) of Kfert	6.407		
d.f.	59.21		
Nfert.Kfert			12.814
d.f.			59.21

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %2012_weight_kg,%2013_weight_kg,%2014_weight_kg

Stratum	d.f.	s.e.	cv%
rep	2	6.706	16.4
rep.Subject	38	6.704	16.4
rep.Subject.Time	80	7.455	18.2

Appendix 4.2: Chapter 4 (N x K trial) soil statistical analysis

Analysis of variance

Variate: %2012_K_mg_L,%2013_K_mg_L,%2014_K_mg_L

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	24805.7	12402.9	8.64	
rep.Subject stratum					
N_fert	3	20320.4	6773.5	4.72	0.007
K_fert	4	75679.7	18919.9	13.17	<.001
N_fert.K_fert	12	10268.1	855.7	0.60	0.832
Residual	38	54570.7	1436.1	2.70	
rep.Subject.Time stratum					
d.f. correction factor 0.8696					
Time	2	34609.7	17304.8	32.58	<.001
Time.N_fert	6	5461.8	910.3	1.71	0.140
Time.K_fert	8	12337.4	1542.2	2.90	0.010
Time.N_fert.K_fert	24	15836.9	659.9	1.24	0.246
Residual	80	42492.9	531.2		
Total	179	296383.3			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 2	39.7	s.e. 17.4
rep 1 Subject 10	49.7	s.e. 17.4
rep 1 Subject 10 Time %2012_K_mg_L	-49.7	s.e. 15.4
rep 1 Subject 10 Time %2014_K_mg_L	61.3	s.e. 15.4

Tables of means

Variate: %2012_K_mg_L,%2013_K_mg_L,%2014_K_mg_L

Grand mean 115.9

	Time %2012_K_mg_L	%2013_K_mg_L	%2014_K_mg_L		
	118.1	97.9	131.7		
N_fert	N1	N2	N3	N4	
	126.5	119.8	119.1	98.2	
K_fert	K1	K2	K3	K4	K5
	88.2	100.7	113.2	133.3	144.0

Time	N_fert	N1	N2	N3	N4
%2012_K_mg_L		122.5	116.7	125.5	107.7
%2013_K_mg_L		104.5	108.7	98.7	79.7
%2014_K_mg_L		152.5	133.9	133.0	107.1

Time	K_fert	K1	K2	K3	K4	K5
%2012_K_mg_L		108.4	107.6	108.8	125.8	139.9
%2013_K_mg_L		68.6	80.7	98.8	120.2	121.2
%2014_K_mg_L		87.6	113.8	131.9	154.0	171.0

N_fert	K_fert	K1	K2	K3	K4	K5
N1		100.8	94.4	122.7	153.0	161.7
N2		90.3	114.7	124.2	119.1	150.4
N3		92.3	105.8	110.4	138.6	148.2
N4		69.3	87.8	95.3	122.7	115.8

Time	N_fert	K_fert	K1	K2	K3	K4
%2012_K_mg_L	N1		114.7	107.7	98.3	138.7
	N2		114.3	120.3	118.0	97.0
	N3		111.3	103.0	115.3	151.0
	N4		93.3	99.3	103.3	116.3
%2013_K_mg_L	N1		86.0	71.7	113.3	126.0
	N2		68.7	86.7	123.3	131.0
	N3		66.3	92.0	83.7	130.3
	N4		53.3	72.3	75.0	93.7
%2014_K_mg_L	N1		101.7	104.0	156.3	194.3
	N2		88.0	137.0	131.3	129.3
	N3		99.3	122.3	132.3	134.3
	N4		61.3	91.7	107.7	158.0

Time	N_fert	K_fert	K5
%2012_K_mg_L	N1		153.3
	N2		133.7
	N3		146.7
	N4		126.0
%2013_K_mg_L	N1		125.3
	N2		133.7
	N3		121.3
	N4		104.3
%2014_K_mg_L	N1		206.3
	N2		184.0
	N3		176.7
	N4		117.0

Least significant differences of means (5% level)

Table	Time	N_fert	K_fert	Time N_fert
rep.	60	45	36	15
l.s.d.	8.60	16.17	18.08	21.45
d.f.	69.57	38	38	88.55
Except when comparing means with the same level(s) of N_fert				17.19
d.f.				69.57

Table	Time K_fert	N_fert K_fert	Time N_fert K_fert
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rep.	12	9	3
l.s.d.	23.98	36.16	47.97
d.f.	88.55	38	88.55
Except when comparing means with the same level(s) of			
K_fert	19.22		
d.f.	69.57		
N_fert.K_fert			38.45
d.f.			69.57

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %2012_K_mg_L,%2013_K_mg_L,%2014_K_mg_L

Stratum	d.f.	s.e.	cv%
rep	2	14.38	12.4
rep.Subject	38	21.88	18.9
rep.Subject.Time	80	23.05	19.9

Analysis of variance

Variate: %2012_Nitrogen_%,%2013_Nitrogen_%,%2014_Nitrogen_%

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.0014169	0.0007085	1.22	
rep.Subject stratum					
N_fert	3	0.0004550	0.0001517	0.26	0.853
K_fert	4	0.0014731	0.0003683	0.63	0.642
N_fert.K_fert	12	0.0021769	0.0001814	0.31	0.983
Residual	38	0.0220942	0.0005814	2.67	
rep.Subject.Time stratum					
d.f. correction factor 0.9838					
Time	2	0.0168003	0.0084001	38.54	<.001
Time.N_fert	6	0.0008008	0.0001335	0.61	0.717
Time.K_fert	8	0.0012969	0.0001621	0.74	0.651
Time.N_fert.K_fert	24	0.0072464	0.0003019	1.39	0.144
Residual	80	0.0174389	0.0002180		
Total	179	0.0711994			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 1	0.0250	s.e. 0.0111
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rep 2 Subject 4	-0.0267	s.e. 0.0111
rep 3 Subject 13	-0.0283	s.e. 0.0111
rep 1 Subject 14 Time %2013_Nitrogen_%	0.0278	s.e. 0.0098
rep 3 Subject 4 Time %2013_Nitrogen_%	0.0261	s.e. 0.0098
rep 3 Subject 4 Time %2014_Nitrogen_%	-0.0256	s.e. 0.0098
rep 3 Subject 16 Time %2013_Nitrogen_%	-0.0250	s.e. 0.0098

Tables of means

Variate: %2012_Nitrogen_%,%2013_Nitrogen_%,%2014_Nitrogen_%

Grand mean 0.0689

Time	%2012_Nitrogen_%	%2013_Nitrogen_%	%2014_Nitrogen_%			
	0.0667	0.0584	0.0817			
N_fert	N1	N2	N3	N4		
	0.0696	0.0662	0.0702	0.0698		
K_fert	K1	K2	K3	K4	K5	
	0.0710	0.0649	0.0728	0.0694	0.0667	
Time	N_fert	N1	N2	N3	N4	
%2012_Nitrogen_%		0.0640	0.0657	0.0707	0.0663	
%2013_Nitrogen_%		0.0600	0.0527	0.0603	0.0607	
%2014_Nitrogen_%		0.0847	0.0803	0.0797	0.0823	
Time	K_fert	K1	K2	K3	K4	K5
%2012_Nitrogen_%		0.0667	0.0571	0.0742	0.0679	0.0675
%2013_Nitrogen_%		0.0604	0.0550	0.0625	0.0587	0.0554
%2014_Nitrogen_%		0.0858	0.0825	0.0817	0.0817	0.0771
N_fert	K_fert	K1	K2	K3	K4	K5
N1		0.0722	0.0633	0.0772	0.0700	0.0650
N2		0.0706	0.0617	0.0711	0.0600	0.0678
N3		0.0761	0.0639	0.0728	0.0744	0.0639
N4		0.0650	0.0706	0.0700	0.0733	0.0700
Time	N_fert	K_fert	K1	K2	K3	
%2012_Nitrogen_%	N1		0.0733	0.0467	0.0700	
	N2		0.0700	0.0633	0.0733	
	N3		0.0717	0.0583	0.0783	
	N4		0.0517	0.0600	0.0750	
%2013_Nitrogen_%	N1		0.0500	0.0633	0.0667	
	N2		0.0550	0.0383	0.0667	
	N3		0.0850	0.0483	0.0633	
	N4		0.0517	0.0700	0.0533	
%2014_Nitrogen_%	N1		0.0933	0.0800	0.0950	
	N2		0.0867	0.0833	0.0733	
	N3		0.0717	0.0850	0.0767	
	N4		0.0917	0.0817	0.0817	
Time	N_fert	K_fert	K4	K5		
%2012_Nitrogen_%	N1		0.0683	0.0617		
	N2		0.0533	0.0683		
	N3		0.0783	0.0667		
	N4		0.0717	0.0733		
%2013_Nitrogen_%	N1		0.0600	0.0600		

	N2	0.0500	0.0533
	N3	0.0533	0.0517
	N4	0.0717	0.0567
%2014_Nitrogen_%	N1	0.0817	0.0733
	N2	0.0767	0.0817
	N3	0.0917	0.0733
	N4	0.0767	0.0800

Least significant differences of means (5% level)

Table	Time	N_fert	K_fert	Time N_fert
rep.	60	45	36	15
l.s.d.	0.00538	0.01029	0.01151	0.01339
d.f.	78.71	38	38	91.51
Except when comparing means with the same level(s) of N_fert				0.01076
d.f.				78.71

Table	Time K_fert	N_fert K_fert	Time N_fert K_fert
rep.	12	9	3
l.s.d.	0.01498	0.02301	0.02995
d.f.	91.51	38	91.51
Except when comparing means with the same level(s) of K_fert	0.01203		
d.f.	78.71		
N_fert.K_fert			0.02406
d.f.			78.71

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: %2012_Nitrogen_%,%2013_Nitrogen_%,%2014_Nitrogen_%

Stratum	d.f.	s.e.	cv%
rep	2	0.00344	5.0
rep.Subject	38	0.01392	20.2
rep.Subject.Time	80	0.01476	21.4

Appendix 4.3: Mean (n=9) soil pH(KCl) due to the interaction between nitrogen (N) and potassium (K) treatments over trial duration after harvest

	K0	K50	K100	K150	K200
N0	5.6	5.6	5.7	6.0	6.1
N60	5.8	6.3	5.8	5.7	5.7
N120	5.6	5.4	5.3	5.7	6.0
N180	5.6	5.6	5.9	5.7	5.7

Appendix 4.4: Chapter 4 (N x K trial) leaf statistical analysis

Analysis of variance

Variate: K_%_2012_1st,K_%_2013_1st,K_%_2014_1st

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.3760	0.1880	0.59	
rep.Subject stratum					
N_fert	3	0.9641	0.3214	1.01	0.401
K_fert	4	9.4291	2.3573	7.38	<.001
N_fert.K_fert	12	3.0375	0.2531	0.79	0.655
Residual	38	12.1379	0.3194	1.50	
rep.Subject.Time stratum					
d.f. correction factor 0.9998					
Time	2	42.5761	21.2880	100.19	<.001
Time.N_fert	6	2.2870	0.3812	1.79	0.111
Time.K_fert	8	2.6122	0.3265	1.54	0.158
Time.N_fert.K_fert	24	5.0937	0.2122	1.00	0.478
Residual	80	16.9987	0.2125		
Total	179	95.5123			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 19	-0.601	s.e. 0.260
rep 3 Subject 16	-0.720	s.e. 0.260
rep 2 Subject 12 Time K_%_2012_1st	0.857	s.e. 0.307
rep 2 Subject 19 Time K_%_2013_1st	0.788	s.e. 0.307
rep 2 Subject 19 Time K_%_2014_1st	-1.037	s.e. 0.307
rep 3 Subject 4 Time K_%_2014_1st	0.825	s.e. 0.307

Tables of means

Variate: K_%_2012_1st,K_%_2013_1st,K_%_2014_1st

Grand mean 4.328

Time	K_%_2012_1st	K_%_2013_1st	K_%_2014_1st	
	4.874	4.417	3.692	
N_fert	N1	N2	N3	N4
	4.418	4.355	4.321	4.216

	K_fert	K1	K2	K3	K4	K5
		3.965	4.191	4.361	4.526	4.595
Time	N_fert	N1	N2	N3	N4	
K_%_2012_1st		4.799	4.850	4.905	4.940	
K_%_2013_1st		4.622	4.437	4.509	4.101	
K_%_2014_1st		3.833	3.778	3.550	3.607	

Time	K_fert	K1	K2	K3	K4	K5
K_%_2012_1st		4.670	4.595	5.006	5.004	5.092
K_%_2013_1st		3.865	4.254	4.350	4.732	4.886
K_%_2014_1st		3.361	3.723	3.729	3.840	3.809

N_fert	K_fert	K1	K2	K3	K4	K5
N1		4.122	4.087	4.471	4.825	4.587
N2		4.050	4.358	4.414	4.355	4.600
N3		3.687	4.275	4.282	4.542	4.819
N4		4.003	4.043	4.279	4.381	4.375

Time	N_fert	K_fert	K1	K2	K3	K4
K_%_2012_1st	N1		4.318	4.337	4.934	5.529
	N2		4.357	4.717	5.160	4.817
	N3		4.892	4.545	4.822	4.902
	N4		5.115	4.782	5.108	4.767
K_%_2013_1st	N1		4.190	4.133	4.658	5.089
	N2		4.263	4.379	4.301	4.546
	N3		3.530	4.689	4.349	4.760
	N4		3.475	3.814	4.090	4.535
K_%_2014_1st	N1		3.857	3.790	3.820	3.856
	N2		3.528	3.978	3.779	3.701
	N3		2.641	3.591	3.676	3.966
	N4		3.421	3.532	3.640	3.839

Time	N_fert	K_fert	K5
K_%_2012_1st	N1		4.878
	N2		5.198
	N3		5.364
	N4		4.927
K_%_2013_1st	N1		5.039
	N2		4.697
	N3		5.216
	N4		4.592
K_%_2014_1st	N1		3.845
	N2		3.906
	N3		3.878
	N4		3.606

Least significant differences of means (5% level)

Table	Time	N_fert	K_fert	Time N_fert
rep.	60	45	36	15
l.s.d.	0.1675	0.2412	0.2697	0.3604
d.f.	79.98	38	38	112.10
Except when comparing means with the same level(s) of N_fert				0.3350
d.f.				79.98

Table	Time	N_fert	Time
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	K_fert	K_fert	N_fert K_fert
rep.	12	9	3
l.s.d.	0.4029	0.5393	0.8059
d.f.	112.10	38	112.10
Except when comparing means with the same level(s) of			
K_fert	0.3745		
d.f.	79.98		
N_fert.K_fert			0.7490
d.f.			79.98

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: K_%_2012_1st,K_%_2013_1st,K_%_2014_1st

Stratum	d.f.	s.e.	cv%
rep	2	0.0560	1.3
rep.Subject	38	0.3263	7.5
rep.Subject.Time	80	0.4610	10.7

Analysis of variance

Variate: K_%_2012_2nd,K_%_2013_2nd,K_%_2014_2nd

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	2.0922	1.0461	3.16	
rep.Subject stratum					
N_fert	3	2.8993	0.9664	2.92	0.046
K_fert	4	6.7910	1.6977	5.14	0.002
N_fert.K_fert	12	2.5843	0.2154	0.65	0.785
Residual	38	12.5630	0.3306	1.79	
rep.Subject.Time stratum					
d.f. correction factor 0.8335					
Time	2	117.5765	58.7883	318.92	<.001
Time.N_fert	6	2.0499	0.3417	1.85	0.114
Time.K_fert	8	2.6000	0.3250	1.76	0.113
Time.N_fert.K_fert	24	6.3609	0.2650	1.44	0.136
Residual	80	14.7470	0.1843		
Total	179	170.2640			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 2	0.601	s.e. 0.264
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rep 2 Subject 6	-0.793	s.e. 0.264
rep 3 Subject 14	0.660	s.e. 0.264
rep 1 Subject 6 Time K_%_2014_2nd	-0.898	s.e. 0.286
rep 2 Subject 6 Time K_%_2014_2nd	-0.719	s.e. 0.286
rep 3 Subject 8 Time K_%_2014_2nd	0.726	s.e. 0.286

Tables of means

Variate: K_%_2012_2nd,K_%_2013_2nd,K_%_2014_2nd

Grand mean 3.850

Time	K_%_2012_2nd	K_%_2013_2nd	K_%_2014_2nd			
	4.695	2.761	4.093			
N_fert	N1	N2	N3	N4		
	3.988	3.896	3.871	3.643		
K_fert	K1	K2	K3	K4	K5	
	3.588	3.796	3.729	4.004	4.131	
Time	N_fert	N1	N2	N3	N4	
K_%_2012_2nd		4.659	4.651	4.875	4.595	
K_%_2013_2nd		2.937	2.793	2.764	2.549	
K_%_2014_2nd		4.369	4.244	3.974	3.786	
Time	K_fert	K1	K2	K3	K4	K5
K_%_2012_2nd		4.650	4.588	4.625	4.818	4.793
K_%_2013_2nd		2.368	2.659	2.795	2.917	3.065
K_%_2014_2nd		3.747	4.140	3.767	4.278	4.533
N_fert	K_fert	K1	K2	K3	K4	K5
N1		3.759	3.801	3.853	4.126	4.402
N2		3.737	4.129	3.613	3.903	4.096
N3		3.477	3.661	3.930	4.083	4.205
N4		3.380	3.592	3.521	3.905	3.818
Time	N_fert	K_fert	K1	K2	K3	K4
K_%_2012_2nd	N1		4.734	4.763	4.470	4.599
	N2		4.846	4.562	4.541	4.649
	N3		4.655	4.444	5.034	5.244
	N4		4.366	4.583	4.456	4.780
K_%_2013_2nd	N1		2.741	2.515	2.977	3.362
	N2		2.587	3.018	2.578	2.785
	N3		2.350	2.673	2.724	2.813
	N4		1.792	2.430	2.900	2.706
K_%_2014_2nd	N1		3.802	4.124	4.110	4.417
	N2		3.779	4.806	3.720	4.276
	N3		3.426	3.868	4.031	4.193
	N4		3.981	3.762	3.207	4.228
Time	N_fert	K_fert	K5			
K_%_2012_2nd	N1		4.728			
	N2		4.655			
	N3		4.998			
	N4		4.791			
K_%_2013_2nd	N1		3.089			
	N2		2.995			

	N3	3.263
	N4	2.915
K_%_2014_2nd	N1	5.391
	N2	4.638
	N3	4.354
	N4	3.750

Least significant differences of means (5% level)

Table	Time	N_fert	K_fert	Time N_fert
rep.	60	45	36	15
l.s.d.	0.1614	0.2454	0.2744	0.3610
d.f.	66.68	38	38	99.50
Except when comparing means with the same level(s) of N_fert				0.3228
d.f.				66.68

Table	Time K_fert	N_fert K_fert	Time N_fert K_fert
rep.	12	9	3
l.s.d.	0.4036	0.5487	0.8071
d.f.	99.50	38	99.50
Except when comparing means with the same level(s) of K_fert	0.3609		
d.f.	66.68		
N_fert.K_fert			0.7219
d.f.			66.68

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: K_%_2012_2nd,K_%_2013_2nd,K_%_2014_2nd

Stratum	d.f.	s.e.	cv%
rep	2	0.1320	3.4
rep.Subject	38	0.3320	8.6
rep.Subject.Time	80	0.4293	11.2

Analysis of variance

Variate: N_%_2012_1st,N_%_2013_1st,N_%_2014_1st

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	10.6813	5.3407	26.89	
rep.Subject stratum					
N_fert	3	3.5303	1.1768	5.92	0.002
K_fert	4	0.3213	0.0803	0.40	0.804
N_fert.K_fert	12	2.0904	0.1742	0.88	0.576
Residual	38	7.5482	0.1986	1.31	

rep.Subject.Time stratum

d.f. correction factor 0.9965

Time	2	13.5047	6.7524	44.40	<.001
Time.N_fert	6	0.9879	0.1646	1.08	0.380
Time.K_fert	8	1.1448	0.1431	0.94	0.488
Time.N_fert.K_fert	24	5.3197	0.2217	1.46	0.109
Residual	80	12.1678	0.1521		
Total	179	57.2963			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 3	0.469	s.e.	0.205
rep 1 Subject 2 Time N_%_2013_1st	-0.893	s.e.	0.260
rep 1 Subject 4 Time N_%_2013_1st	-0.697	s.e.	0.260

Tables of means

Variate: N_%_2012_1st,N_%_2013_1st,N_%_2014_1st

Grand mean 3.462

Time	N_%_2012_1st	N_%_2013_1st	N_%_2014_1st			
	3.340	3.206	3.842			
N_fert	N1	N2	N3	N4		
	3.282	3.372	3.576	3.620		
K_fert	K1	K2	K3	K4	K5	
	3.491	3.393	3.515	3.472	3.441	
Time	N_fert	N1	N2	N3	N4	
N_%_2012_1st		3.046	3.213	3.589	3.511	
N_%_2013_1st		3.054	3.111	3.223	3.435	
N_%_2014_1st		3.747	3.792	3.915	3.914	
Time	K_fert	K1	K2	K3	K4	K5
N_%_2012_1st		3.461	3.205	3.535	3.336	3.162
N_%_2013_1st		3.150	3.136	3.208	3.254	3.280
N_%_2014_1st		3.860	3.839	3.803	3.827	3.882
N_fert	K_fert	K1	K2	K3	K4	K5
N1		3.255	3.087	3.402	3.414	3.252
N2		3.564	3.361	3.207	3.462	3.265
N3		3.488	3.640	3.629	3.435	3.686
N4		3.655	3.484	3.823	3.577	3.562
Time	N_fert	K_fert	K1	K2	K3	K4
N_%_2012_1st	N1		2.897	2.781	3.428	3.149
	N2		3.526	3.397	3.241	3.076

	N3	3.363	3.617	3.799	3.395
	N4	4.060	3.024	3.672	3.723
N_%_2013_1st	N1	3.099	2.948	2.961	3.084
	N2	3.029	3.134	2.920	3.228
	N3	3.086	3.040	3.301	3.349
	N4	3.388	3.420	3.650	3.353
N_%_2014_1st	N1	3.769	3.532	3.817	4.010
	N2	4.137	3.553	3.459	4.080
	N3	4.017	4.262	3.787	3.562
	N4	3.518	4.008	4.147	3.655
Time	N_fert	K_fert	K5		
N_%_2012_1st	N1		2.973		
	N2		2.826		
	N3		3.770		
	N4		3.079		
N_%_2013_1st	N1		3.177		
	N2		3.240		
	N3		3.340		
	N4		3.365		
N_%_2014_1st	N1		3.607		
	N2		3.729		
	N3		3.950		
	N4		4.241		

Least significant differences of means (5% level)

Table	Time	N_fert	K_fert	Time N_fert
rep.	60	45	36	15
l.s.d.	0.1418	0.1902	0.2127	0.2963
d.f.	79.72	38	38	114.97
Except when comparing means with the same level(s) of N_fert				0.2836
d.f.				79.72

Table	Time K_fert	N_fert K_fert	Time N_fert K_fert
rep.	12	9	3
l.s.d.	0.3313	0.4253	0.6625
d.f.	114.97	38	114.97
Except when comparing means with the same level(s) of K_fert			0.3171
d.f.			79.72
N_fert.K_fert			0.6341
d.f.			79.72

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: N_%_2012_1st,N_%_2013_1st,N_%_2014_1st

Stratum	d.f.	s.e.	cv%
rep	2	0.2983	8.6

rep.Subject	38	0.2573	7.4
rep.Subject.Time	80	0.3900	11.3

Analysis of variance

Variate: N_%_2012_2nd,N_%_2013_2nd,N_%_2014_2nd

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.01075	0.00537	0.05	
rep.Subject stratum					
N_fert	3	0.06087	0.02029	0.20	0.894
K_fert	4	0.27078	0.06770	0.68	0.612
N_fert.K_fert	12	0.89274	0.07439	0.74	0.700
Residual	38	3.79877	0.09997	1.63	
rep.Subject.Time stratum					
d.f. correction factor 0.8720					
Time	2	47.92617	23.96308	391.84	<.001
Time.N_fert	6	0.41006	0.06834	1.12	0.360
Time.K_fert	8	0.61030	0.07629	1.25	0.289
Time.N_fert.K_fert	24	1.44935	0.06039	0.99	0.489
Residual	80	4.89248	0.06116		
Total	179	60.32225			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 5	0.392	s.e. 0.145
rep 3 Subject 5 Time N_%_2012_2nd	-0.433	s.e. 0.165

Tables of means

Variate: N_%_2012_2nd,N_%_2013_2nd,N_%_2014_2nd

Grand mean 2.565

Time	N_%_2012_2nd	N_%_2013_2nd	N_%_2014_2nd		
	3.209	1.946	2.540		
N_fert	N1	N2	N3	N4	
	2.543	2.556	2.566	2.593	
K_fert	K1	K2	K3	K4	K5
	2.529	2.508	2.584	2.605	2.597
Time	N_fert	N1	N2	N3	N4

N_%_2012_2nd	3.185	3.207	3.270	3.173
N_%_2013_2nd	1.968	1.952	1.843	2.019
N_%_2014_2nd	2.476	2.510	2.585	2.587

Time	K_fert	K1	K2	K3	K4	K5
N_%_2012_2nd		3.078	3.139	3.214	3.392	3.221
N_%_2013_2nd		1.913	1.891	1.985	1.932	2.007
N_%_2014_2nd		2.596	2.495	2.552	2.491	2.564

N_fert	K_fert	K1	K2	K3	K4	K5
N1		2.483	2.434	2.501	2.773	2.525
N2		2.613	2.524	2.477	2.577	2.590
N3		2.515	2.507	2.658	2.545	2.605
N4		2.506	2.568	2.699	2.525	2.668

Time	N_fert	K_fert	K1	K2	K3	K4
N_%_2012_2nd	N1		2.868	3.140	3.021	3.757
	N2		3.311	3.334	3.018	3.231
	N3		3.057	3.039	3.512	3.294
	N4		3.077	3.044	3.305	3.285
N_%_2013_2nd	N1		2.013	1.808	1.975	2.049
	N2		1.965	1.869	1.862	2.049
	N3		1.817	1.883	1.892	1.786
	N4		1.856	2.003	2.212	1.846
N_%_2014_2nd	N1		2.567	2.353	2.507	2.514
	N2		2.563	2.368	2.549	2.453
	N3		2.671	2.600	2.569	2.554
	N4		2.584	2.658	2.581	2.444

Time	N_fert	K_fert	K5
N_%_2012_2nd	N1		3.141
	N2		3.138
	N3		3.449
	N4		3.155
N_%_2013_2nd	N1		1.995
	N2		2.015
	N3		1.836
	N4		2.181
N_%_2014_2nd	N1		2.439
	N2		2.618
	N3		2.532
	N4		2.668

Least significant differences of means (5% level)

Table	Time	N_fert	K_fert	Time N_fert
rep.	60	45	36	15
l.s.d.	0.0922	0.1349	0.1509	0.2018
d.f.	69.76	38	38	103.49
Except when comparing means with the same level(s) of N_fert				0.1844
d.f.				69.76

Table	Time K_fert	N_fert K_fert	Time N_fert K_fert
rep.	12	9	3
l.s.d.	0.2257	0.3017	0.4513

d.f.	103.49	38	103.49
Except when comparing means with the same level(s) of			
K_fert	0.2062		
d.f.	69.76		
N_fert.K_fert			0.4123
d.f.			69.76

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: N_%_2012_2nd,N_%_2013_2nd,N_%_2014_2nd

Stratum	d.f.	s.e.	cv%
rep	2	0.0095	0.4
rep.Subject	38	0.1825	7.1
rep.Subject.Time	80	0.2473	9.6

Appendix 4.5: Chapter 4 (N x K trial) root statistical analysis

Analysis of variance

Variate: Root_N %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.077949	0.038975	5.35	
rep.*Units* stratum					
K_fert	4	0.032744	0.008186	1.12	0.360
Lin	1	0.009338	0.009338	1.28	0.265
Quad	1	0.007900	0.007900	1.08	0.304
Deviations	2	0.015505	0.007753	1.06	0.355
N_fert	3	0.045448	0.015149	2.08	0.119
Lin	1	0.026431	0.026431	3.63	0.064
Quad	1	0.000347	0.000347	0.05	0.828
Deviations	1	0.018670	0.018670	2.56	0.118
K_fert.N_fert	12	0.147429	0.012286	1.69	0.109
Lin.Lin	1	0.009608	0.009608	1.32	0.258
Quad.Lin	1	0.003349	0.003349	0.46	0.502
Lin.Quad	1	0.013699	0.013699	1.88	0.178
Dev.Lin	2	0.007060	0.003530	0.48	0.620
Quad.Quad	1	0.029493	0.029493	4.05	0.051
Lin.Dev	1	0.017768	0.017768	2.44	0.127
Dev.Quad	2	0.061389	0.030695	4.21	0.022
Quad.Dev	1	0.001869	0.001869	0.26	0.616
Deviations	2	0.003194	0.001597	0.22	0.804
Residual	38	0.277047	0.007291		
Total	59	0.580617			

Message: the following units have large residuals.

rep 2 *units* 3	-0.159	s.e. 0.068
rep 2 *units* 18	0.157	s.e. 0.068

Tables of means

Variate: Root_N %

Grand mean 0.446

K_fert	0	50	100	150	200
	0.452	0.405	0.455	0.444	0.476
N_fert	0	60	120	180	
	0.424	0.416	0.482	0.464	
K_fert	N_fert	0	60	120	180
0		0.341	0.455	0.597	0.414
50		0.418	0.303	0.395	0.504
100		0.451	0.403	0.508	0.459
150		0.457	0.440	0.452	0.426
200		0.451	0.478	0.458	0.518

Least significant differences of means (5% level)

Table	K_fert	N_fert	K_fert N_fert
rep.	12	15	3
d.f.	38	38	38
l.s.d.	0.0706	0.0631	0.1411

Stratum standard errors and coefficients of variation

Variate: Root_N %

Stratum	d.f.	s.e.	cv%
rep	2	0.0441	9.9
rep.*Units*	38	0.0854	19.1

Analysis of variance

Variate: Root_K %

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.09134	0.04567	1.18	
rep.*Units* stratum					
K_fert	4	0.59355	0.14839	3.82	0.010
Lin	1	0.34272	0.34272	8.82	0.005
Quad	1	0.12418	0.12418	3.20	0.082
Deviations	2	0.12664	0.06332	1.63	0.209
N_fert	3	0.11071	0.03690	0.95	0.426
Lin	1	0.08501	0.08501	2.19	0.147
Quad	1	0.01244	0.01244	0.32	0.575
Deviations	1	0.01327	0.01327	0.34	0.562
K_fert.N_fert	12	0.44140	0.03678	0.95	0.513
Lin.Lin	1	0.03559	0.03559	0.92	0.345
Quad.Lin	1	0.00825	0.00825	0.21	0.647

Appendix 5.1: Hot water extractable boron methodology

As developed by Berger and Troug (1939) using a soil : water ratio of 1:2.

Weigh out 25 g of air-dried <2 mm sieved soil into 250 ml beakers and add accurately 50 ml 10 mM CaCl₂ solution or deionised water. Record the mass of the beaker, watch glass, soil and solution and record this as ‘before boiling’. Boil soil and solution for five minutes on a hot plate, swirl the samples during boiling. Remove the samples, reweigh and record as “after boiling”. Filter the samples through suitable filter paper and calibrate the ICP at wavelength 249.77 nm with calibration standards. Run all the samples but without soil to determine B blanks. The blank figures are subtracted from the ICP results. Calculate as follows: Soil B mg kg⁻¹ = ICP reading minus blank x dilution factor (ie. 50 – mass lost by evaporation / 25).

Appendix 5.2: Chapter 5 (B trial) yield statistical analysis

Analysis of variance

Variate: %2013_Weight_Kg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	699.15	233.05	7.34	
rep.*Units* stratum					
Boron	7	20.98	3.00	0.09	0.998
Apply	1	12.43	12.43	0.39	0.535
Boron.Apply	7	111.86	15.98	0.50	0.827
Residual	45	1428.63	31.75		
Total	63	2273.04			

Message: the following units have large residuals.

rep 2 *units* 3	-10.93	s.e. 4.72
rep 4 *units* 8	12.92	s.e. 4.72

Tables of means

Variate: %2013_Weight_Kg

Grand mean 33.77

Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	34.62	34.30	33.92	33.17	32.84	33.30	33.85
Boron	3.5kg/ha						
	34.14						

Apply	soil	leaf	
	34.21	33.33	
Boron	Apply	soil	leaf
0kg/ha		37.15	32.10
0.5kg/ha		36.55	32.05
1kg/ha		33.65	34.20
1.5kg/ha		33.95	32.40
2kg/ha		33.10	32.58
2.5kg/ha		31.65	34.95
3kg/ha		34.20	33.50
3.5kg/ha		33.42	34.85

Least significant differences of means (5% level)

Table	Boron	Apply	Boron Apply
rep.	8	32	4
d.f.	45	45	45
l.s.d.	5.674	2.837	8.025

Stratum standard errors and coefficients of variation

Variate: %2013_Weight_Kg

Stratum	d.f.	s.e.	cv%
rep	3	3.816	11.3
rep.*Units*	45	5.634	16.7

Analysis of variance

Variate: %2014_weight_Kg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	331.61	110.54	3.70	
rep.*Units* stratum					
Boron	7	102.45	14.64	0.49	0.837
Apply	1	6.50	6.50	0.22	0.643
Boron.Apply	7	97.41	13.92	0.47	0.854
Residual	45	1343.43	29.85		
Total	63	1881.40			

Message: the following units have large residuals.

rep 4 *units* 9	12.56	s.e. 4.58
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Tables of means

Variate: %2014_weight_Kg

Grand mean 37.68

Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	38.38	38.25	36.23	37.25	35.50	37.65	39.80
Boron	3.5kg/ha						
	38.35						
Apply	soil	leaf					
	37.99	37.36					
Boron	Apply	soil	leaf				
0kg/ha		38.85	37.90				
0.5kg/ha		38.25	38.25				
1kg/ha		36.15	36.30				
1.5kg/ha		38.50	36.00				
2kg/ha		35.00	36.00				
2.5kg/ha		40.70	34.60				
3kg/ha		39.35	40.25				
3.5kg/ha		37.15	39.55				

Least significant differences of means (5% level)

Table	Boron	Apply	Boron Apply
rep.	8	32	4
d.f.	45	45	45
l.s.d.	5.502	2.751	7.782

Stratum standard errors and coefficients of variation

Variate: %2014_weight_Kg

Stratum	d.f.	s.e.	cv%
rep	3	2.628	7.0
rep.*Units*	45	5.464	14.5

Appendix 5.3: Chapter 5 (B trial) soil statistical analysis

Analysis of variance

Variate: B_mg_kg_2013,B_mg_kg_2014 (0-15cm depth)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	0.038439	0.012813	4.13	
rep.Subject stratum					
Boron	7	0.354228	0.050604	16.29	<.001
Apply	1	0.005778	0.005778	1.86	0.179
Boron.Apply	7	0.035478	0.005068	1.63	0.151

Residual	45	0.139773	0.003106	1.59	
rep.Subject.Time stratum					
d.f. correction factor 1.0000					
Time	1	0.046512	0.046512	23.84	<.001
Time.Boron	7	0.017506	0.002501	1.28	0.279
Time.Apply	1	0.140450	0.140450	72.00	<.001
Time.Boron.Apply	7	0.053169	0.007596	3.89	0.002
Residual	48	0.093638	0.001951		
Total	127	0.924972			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 12 Time B_mg_kg_2013	-0.0806	s.e.	0.0270
rep 2 Subject 12 Time B_mg_kg_2014	0.0806	s.e.	0.0270

Tables of means

Variate: B_mg_kg_2013,B_mg_kg_2014

Grand mean 0.1933

Time	B_mg_kg_2013	B_mg_kg_2014					
	0.1742	0.2123					
Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	0.1016	0.1300	0.1791	0.1872	0.2156	0.2181	0.2484
Boron	3.5kg/ha						
	0.2663						
Apply	soil	leaf					
	0.1866	0.2000					
Time	Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	
B_mg_kg_2013		0.0931	0.1238	0.1456	0.1719	0.1850	
B_mg_kg_2014		0.1100	0.1363	0.2125	0.2025	0.2463	
Time	Boron	2.5kg/ha	3kg/ha	3.5kg/ha			
B_mg_kg_2013		0.1813	0.2356	0.2575			
B_mg_kg_2014		0.2550	0.2613	0.2750			
Time	Apply	soil	leaf				
B_mg_kg_2013		0.1344	0.2141				
B_mg_kg_2014		0.2388	0.1859				
Boron	Apply	soil	leaf				
0kg/ha		0.0975	0.1056				
0.5kg/ha		0.1181	0.1419				

1kg/ha	0.2106	0.1475
1.5kg/ha	0.1819	0.1925
2kg/ha	0.2063	0.2250
2.5kg/ha	0.2038	0.2325
3kg/ha	0.2163	0.2806
3.5kg/ha	0.2581	0.2744

Time	Boron	Apply	soil	leaf
B_mg_kg_2013	0kg/ha		0.0850	0.1013
	0.5kg/ha		0.1063	0.1413
	1kg/ha		0.1363	0.1550
	1.5kg/ha		0.1263	0.2175
	2kg/ha		0.1475	0.2225
	2.5kg/ha		0.1375	0.2250
	3kg/ha		0.1575	0.3138
	3.5kg/ha		0.1788	0.3363
B_mg_kg_2014	0kg/ha		0.1100	0.1100
	0.5kg/ha		0.1300	0.1425
	1kg/ha		0.2850	0.1400
	1.5kg/ha		0.2375	0.1675
	2kg/ha		0.2650	0.2275
	2.5kg/ha		0.2700	0.2400
	3kg/ha		0.2750	0.2475
	3.5kg/ha		0.3375	0.2125

Least significant differences of means (5% level)

Table	Time	Boron	Apply	Time Boron
rep.	64	16	64	8
l.s.d.	0.01570	0.03969	0.01984	0.04997
d.f.	48	45	45	87.07
Except when comparing means with the same level(s) of Boron				0.04440
d.f.				48

Table	Time Apply	Boron Apply	Time Boron Apply
rep.	32	8	4
l.s.d.	0.02499	0.05613	0.07067
d.f.	87.07	45	87.07
Except when comparing means with the same level(s) of Apply	0.02220		
d.f.	48		
Boron.Apply			0.06279
d.f.			48

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: B_mg_kg_2013,B_mg_kg_2014

Stratum	d.f.	s.e.	cv%
rep	3	0.02001	10.4
rep.Subject	45	0.03941	20.4

Boron	3.5kg/ha					
	0.0744					
Apply	soil	leaf				
	0.0537	0.0511				
Time	Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha
B_mg_kg_2012		0.0312	0.0225	0.0275	0.0312	0.0300
B_mg_kg_2014_1		0.0437	0.0500	0.0662	0.0600	0.0825
Time	Boron	2.5kg/ha	3kg/ha	3.5kg/ha		
B_mg_kg_2012		0.0262	0.0237	0.0312		
B_mg_kg_2014_1		0.0850	0.1100	0.1175		
Time	Apply	soil	leaf			
B_mg_kg_2012		0.0284	0.0275			
B_mg_kg_2014_1		0.0791	0.0747			
Boron	Apply	soil	leaf			
0kg/ha		0.0362	0.0387			
0.5kg/ha		0.0362	0.0362			
1kg/ha		0.0487	0.0450			
1.5kg/ha		0.0525	0.0387			
2kg/ha		0.0587	0.0537			
2.5kg/ha		0.0487	0.0625			
3kg/ha		0.0687	0.0650			
3.5kg/ha		0.0800	0.0687			
Time	Boron	Apply	soil	leaf		
B_mg_kg_2012	0kg/ha		0.0300	0.0325		
	0.5kg/ha		0.0225	0.0225		
	1kg/ha		0.0275	0.0275		
	1.5kg/ha		0.0325	0.0300		
	2kg/ha		0.0275	0.0325		
	2.5kg/ha		0.0300	0.0225		
	3kg/ha		0.0250	0.0225		
	3.5kg/ha		0.0325	0.0300		
B_mg_kg_2014_1	0kg/ha		0.0425	0.0450		
	0.5kg/ha		0.0500	0.0500		
	1kg/ha		0.0700	0.0625		
	1.5kg/ha		0.0725	0.0475		
	2kg/ha		0.0900	0.0750		
	2.5kg/ha		0.0675	0.1025		
	3kg/ha		0.1125	0.1075		
	3.5kg/ha		0.1275	0.1075		

Least significant differences of means (5% level)

Table	Time	Boron	Apply	Time Boron
rep.	64	16	64	8
l.s.d.	0.00875	0.02047	0.01024	0.02658
d.f.	48	45	45	89.86
Except when comparing means with the same level(s) of Boron				0.02474
d.f.				48

Table	Time Apply	Boron Apply	Time Boron
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rep 2 Subject 12 Time DRAWDOWN_B_2013_2102	-0.0919	s.e. 0.0309
rep 2 Subject 12 Time DRAWDOWN_B_2014_2104	0.0919	s.e. 0.0309
rep 4 Subject 9 Time DRAWDOWN_B_2013_2102	-0.0800	s.e. 0.0309
rep 4 Subject 9 Time DRAWDOWN_B_2014_2104	0.0800	s.e. 0.0309

Tables of means

Variate: DRAWDOWN_B_2013_2102,DRAWDOWN_B_2014_2104

Grand mean 0.1409

Time		DRAWDOWN_B_2013_2102	DRAWDOWN_B_2014_2104												
		0.1463	0.1355												
Boron	0kg/ha	0.0641	0.5kg/ha	0.0938	1kg/ha	0.1322	1.5kg/ha	0.1416	2kg/ha	0.1594	2.5kg/ha	0.1625	3kg/ha	0.1816	
Boron	3.5kg/ha	0.1919													
Apply	soil	0.1328		leaf	0.1489										
	Time	Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha								
DRAWDOWN_B_2013_2102			0.0619	0.1013	0.1181	0.1406	0.1550								
DRAWDOWN_B_2014_2104			0.0663	0.0863	0.1463	0.1425	0.1638								
	Time	Boron	2.5kg/ha	3kg/ha	3.5kg/ha										
DRAWDOWN_B_2013_2102			0.1550	0.2119	0.2263										
DRAWDOWN_B_2014_2104			0.1700	0.1513	0.1575										
	Time	Apply	soil	leaf											
DRAWDOWN_B_2013_2102			0.1059	0.1866											
DRAWDOWN_B_2014_2104			0.1597	0.1113											
Boron	Apply	soil	leaf												
0kg/ha			0.0613	0.0669											
0.5kg/ha			0.0819	0.1056											
1kg/ha			0.1619	0.1025											
1.5kg/ha			0.1294	0.1538											
2kg/ha			0.1475	0.1713											
2.5kg/ha			0.1550	0.1700											
3kg/ha			0.1475	0.2156											
3.5kg/ha			0.1781	0.2056											
	Time	Boron	Apply	soil	leaf										
DRAWDOWN_B_2013_2102				0.0550	0.0688										
			0.5kg/ha	0.0838	0.1188										
			1kg/ha	0.1088	0.1275										
			1.5kg/ha	0.0938	0.1875										
			2kg/ha	0.1200	0.1900										
			2.5kg/ha	0.1075	0.2025										
			3kg/ha	0.1325	0.2913										
			3.5kg/ha	0.1463	0.3063										
DRAWDOWN_B_2014_2104			0kg/ha	0.0675	0.0650										
			0.5kg/ha	0.0800	0.0925										
			1kg/ha	0.2150	0.0775										
			1.5kg/ha	0.1650	0.1200										

2kg/ha	0.1750	0.1525
2.5kg/ha	0.2025	0.1375
3kg/ha	0.1625	0.1400
3.5kg/ha	0.2100	0.1050

Least significant differences of means (5% level)

Table	Time	Boron	Apply	Time Boron
rep.	64	16	64	8
l.s.d.	0.01793	0.04176	0.02088	0.05433
d.f.	48	45	45	90.01
Except when comparing means with the same level(s) of Boron				0.05070
d.f.				48

Table	Time Apply	Boron Apply	Time Boron Apply
rep.	32	8	4
l.s.d.	0.02717	0.05906	0.07683
d.f.	90.01	45	90.01
Except when comparing means with the same level(s) of Apply	0.02535		
d.f.	48		
Boron.Apply			0.07170
d.f.			48

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: DRAWDOWN_B_2013_2102,DRAWDOWN_B_2014_2104

Stratum	d.f.	s.e.	cv%
rep	3	0.02092	14.9
rep.Subject	45	0.04147	29.4
rep.Subject.Time	48	0.05043	35.8

Analysis of variance (subsoil initial and final)

Variate: B_mg_kg_2012,B_mg_kg_2014_1

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	0.0012148	0.0004049	0.49	
rep.Subject stratum					
Boron	7	0.0204305	0.0029186	3.53	0.004
Apply	1	0.0002258	0.0002258	0.27	0.604
Boron.Apply	7	0.0020305	0.0002901	0.35	0.925
Residual	45	0.0371977	0.0008266	1.37	
rep.Subject.Time stratum					
d.f. correction factor 1.0000					
Time	1	0.0765383	0.0765383	126.41	<.001
Time.Boron	7	0.0207680	0.0029669	4.90	<.001
Time.Apply	1	0.0000945	0.0000945	0.16	0.694
Time.Boron.Apply	7	0.0029867	0.0004267	0.70	0.668
Residual	48	0.0290625	0.0006055		
Total	127	0.1905492			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 1	0.0559	s.e.	0.0170
rep 2 Subject 1 Time B_mg_kg_2012	-0.0462	s.e.	0.0151
rep 2 Subject 1 Time B_mg_kg_2014_1	0.0462	s.e.	0.0151
rep 2 Subject 9 Time B_mg_kg_2012	0.0375	s.e.	0.0151
rep 2 Subject 9 Time B_mg_kg_2014_1	-0.0375	s.e.	0.0151

Tables of means

Variate: B_mg_kg_2012,B_mg_kg_2014_1

Grand mean 0.0524

Time	B_mg_kg_2012	B_mg_kg_2014_1					
	0.0280	0.0769					
Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	0.0375	0.0362	0.0469	0.0456	0.0562	0.0556	0.0669
Boron	3.5kg/ha						
	0.0744						
Apply	soil	leaf					

0.0537 0.0511

Time	Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha
B_mg_kg_2012		0.0312	0.0225	0.0275	0.0312	0.0300
B_mg_kg_2014_1		0.0437	0.0500	0.0662	0.0600	0.0825

Time	Boron	2.5kg/ha	3kg/ha	3.5kg/ha
B_mg_kg_2012		0.0262	0.0237	0.0312
B_mg_kg_2014_1		0.0850	0.1100	0.1175

Time	Apply	soil	leaf
B_mg_kg_2012		0.0284	0.0275
B_mg_kg_2014_1		0.0791	0.0747

Boron	Apply	soil	leaf
0kg/ha		0.0362	0.0387
0.5kg/ha		0.0362	0.0362
1kg/ha		0.0487	0.0450
1.5kg/ha		0.0525	0.0387
2kg/ha		0.0587	0.0537
2.5kg/ha		0.0487	0.0625
3kg/ha		0.0687	0.0650
3.5kg/ha		0.0800	0.0687

Time	Boron	Apply	soil	leaf
B_mg_kg_2012	0kg/ha		0.0300	0.0325
	0.5kg/ha		0.0225	0.0225
	1kg/ha		0.0275	0.0275
	1.5kg/ha		0.0325	0.0300
	2kg/ha		0.0275	0.0325
	2.5kg/ha		0.0300	0.0225
	3kg/ha		0.0250	0.0225
B_mg_kg_2014_1	0kg/ha		0.0425	0.0450
	0.5kg/ha		0.0500	0.0500
	1kg/ha		0.0700	0.0625
	1.5kg/ha		0.0725	0.0475
	2kg/ha		0.0900	0.0750
	2.5kg/ha		0.0675	0.1025
	3kg/ha		0.1125	0.1075
3.5kg/ha		0.1275	0.1075	

Least significant differences of means (5% level)

Table	Time	Boron	Apply	Time Boron
rep.	64	16	64	8
l.s.d.	0.00875	0.02047	0.01024	0.02658
d.f.	48	45	45	89.86
Except when comparing means with the same level(s) of Boron				0.02474
d.f.				48

Table	Time Apply	Boron Apply	Time Boron Apply
rep.	32	8	4
l.s.d.	0.01329	0.02895	0.03759
d.f.	89.86	45	89.86

Except when comparing means with the same level(s) of
 Apply 0.01237
 d.f. 48
 Boron.Apply 0.03498
 d.f. 48

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: B_mg_kg_2012,B_mg_kg_2014_1

Stratum	d.f.	s.e.	cv%
rep	3	0.00356	6.8
rep.Subject	45	0.02033	38.8
rep.Subject.Time	48	0.02461	46.9

Analysis of variance

Variate: DRAWDOWN_B_2013_2012

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	0.008291	0.002764	2.50	
rep.*Units* stratum					
Boron	7	0.166612	0.023802	21.51	<.001
Apply	1	0.104006	0.104006	94.01	<.001
Boron.Apply	7	0.046556	0.006651	6.01	<.001
Residual	45	0.049784	0.001106		
Total	63	0.375250			

Message: the following units have large residuals.

rep 4 *units* 14	0.0928	s.e. 0.0279
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Tables of means

Variate: DRAWDOWN_B_2013_2102

Grand mean 0.1462

Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	0.0619	0.1012	0.1181	0.1406	0.1550	0.1550	0.2119
Boron	3.5kg/ha						
	0.2263						
Apply	soil	leaf					
	0.1059	0.1866					
Boron	Apply	soil	leaf				
0kg/ha		0.0550	0.0687				
0.5kg/ha		0.0837	0.1187				

1kg/ha	0.1087	0.1275
1.5kg/ha	0.0938	0.1875
2kg/ha	0.1200	0.1900
2.5kg/ha	0.1075	0.2025
3kg/ha	0.1325	0.2913
3.5kg/ha	0.1462	0.3063

Least significant differences of means (5% level)

Table	Boron	Apply	Boron Apply
rep.	8	32	4
d.f.	45	45	45
l.s.d.	0.03350	0.01675	0.04737

Stratum standard errors and coefficients of variation

Variate: DRAWDOWN_B_2013_2102

Stratum	d.f.	s.e.	cv%
rep	3	0.01314	9.0
rep.*Units*	45	0.03326	22.7

Analysis of variance

Variate: DRAWDOWN_B_2014_2104

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	0.043530	0.014510	3.00	
rep.*Units* stratum					
Boron	7	0.080848	0.011550	2.39	0.036
Apply	1	0.037539	0.037539	7.77	0.008
Boron.Apply	7	0.037173	0.005310	1.10	0.380
Residual	45	0.217295	0.004829		
Total	63	0.416386			

Message: the following units have large residuals.

rep 2 *units* 12	0.1711	s.e. 0.0583
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Tables of means

Variate: DRAWDOWN_B_2014_2104

Grand mean 0.1355

Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	0.0662	0.0862	0.1462	0.1425	0.1637	0.1700	0.1512
Boron	3.5kg/ha						

	0.1575		
Apply	soil	leaf	
	0.1597	0.1112	
Boron	Apply	soil	leaf
0kg/ha		0.0675	0.0650
0.5kg/ha		0.0800	0.0925
1kg/ha		0.2150	0.0775
1.5kg/ha		0.1650	0.1200
2kg/ha		0.1750	0.1525
2.5kg/ha		0.2025	0.1375
3kg/ha		0.1625	0.1400
3.5kg/ha		0.2100	0.1050

Least significant differences of means (5% level)

Table	Boron	Apply	Boron Apply
rep.	8	32	4
d.f.	45	45	45
l.s.d.	0.06998	0.03499	0.09897

Stratum standard errors and coefficients of variation

Variate: DRAWDOWN_B_2014_2104

Stratum	d.f.	s.e.	cv%
rep	3	0.03011	22.2
rep.*Units*	45	0.06949	51.3

Analysis of variance

Variate: B_mg_kg_2013 (topsoil)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	0.007070	0.002357	2.33	
rep.*Units* stratum					
Boron	7	0.166548	0.023793	23.50	<.001
Apply	1	0.101602	0.101602	100.36	<.001
Boron.Apply	7	0.043736	0.006248	6.17	<.001
Residual	45	0.045555	0.001012		
Total	63	0.364511			

Message: the following units have large residuals.

rep 4 *units* 14	0.0939	s.e.	0.0267
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Tables of means

Variate: B_mg_kg_2013

Grand mean 0.1742

Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	0.0931	0.1238	0.1456	0.1719	0.1850	0.1813	0.2356
Boron	3.5kg/ha						
	0.2575						
Apply	soil	leaf					
	0.1344	0.2141					
Boron	Apply	soil	leaf				
0kg/ha		0.0850	0.1013				
0.5kg/ha		0.1063	0.1413				
1kg/ha		0.1363	0.1550				
1.5kg/ha		0.1263	0.2175				
2kg/ha		0.1475	0.2225				
2.5kg/ha		0.1375	0.2250				
3kg/ha		0.1575	0.3138				
3.5kg/ha		0.1788	0.3363				

Least significant differences of means (5% level)

Table	Boron	Apply	Boron Apply
rep.	8	32	4
d.f.	45	45	45
l.s.d.	0.03204	0.01602	0.04531

Stratum standard errors and coefficients of variation

Variate: B_mg_kg_2013

Stratum	d.f.	s.e.	cv%
rep	3	0.01214	7.0
rep.*Units*	45	0.03182	18.3

Analysis of variance

Variate: B_mg_kg_2014 (topsoil)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	0.040355	0.013452	3.38	
rep.*Units* stratum					
Boron	7	0.205186	0.029312	7.37	<.001
Apply	1	0.044627	0.044627	11.23	0.002
Boron.Apply	7	0.044911	0.006416	1.61	0.156
Residual	45	0.178870	0.003975		

Total 63 0.513948

Message: the following units have large residuals.

rep 1 *units* 9	-0.1239	s.e. 0.0529
rep 2 *units* 12	0.1411	s.e. 0.0529

Tables of means

Variate: B_mg_kg_2014

Grand mean 0.2123

Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	0.1100	0.1362	0.2125	0.2025	0.2462	0.2550	0.2612
Boron	3.5kg/ha						
	0.2750						
Apply	soil	leaf					
	0.2387	0.1859					
Boron	Apply	soil	leaf				
0kg/ha		0.1100	0.1100				
0.5kg/ha		0.1300	0.1425				
1kg/ha		0.2850	0.1400				
1.5kg/ha		0.2375	0.1675				
2kg/ha		0.2650	0.2275				
2.5kg/ha		0.2700	0.2400				
3kg/ha		0.2750	0.2475				
3.5kg/ha		0.3375	0.2125				

Least significant differences of means (5% level)

Table	Boron	Apply	Boron Apply
rep.	8	32	4
d.f.	45	45	45
l.s.d.	0.06349	0.03175	0.08979

Stratum standard errors and coefficients of variation

Variate: B_mg_kg_2014

Stratum	d.f.	s.e.	cv%
rep	3	0.02900	13.7
rep.*Units*	45	0.06305	29.7

Appendix 5.4: Chapter 5 (B trial) leaf statistical analysis

Analysis of variance

Variate: B_mg_kg_2013_1st,B_mg_kg_2014_1st (60 DAS)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	152.869	50.956	3.48	
rep.Subject stratum					
Boron	7	375.458	53.637	3.66	0.003
Apply	1	30.852	30.852	2.11	0.154
Boron.Apply	7	56.994	8.142	0.56	0.787
Residual	45	659.102	14.647	3.93	
rep.Subject.Time stratum					
d.f. correction factor 1.0000					
Time	1	5.439	5.439	1.46	0.233
Time.Boron	7	24.252	3.465	0.93	0.493
Time.Apply	1	0.601	0.601	0.16	0.690
Time.Boron.Apply	7	16.568	2.367	0.64	0.725
Residual	48	178.901	3.727		
Total	127	1501.036			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 3 Subject 13 Time B_mg_kg_2013_1st	5.36	s.e.	1.18
rep 3 Subject 13 Time B_mg_kg_2014_1st	-5.36	s.e.	1.18
rep 4 Subject 4 Time B_mg_kg_2013_1st	2.83	s.e.	1.18
rep 4 Subject 4 Time B_mg_kg_2014_1st	-2.83	s.e.	1.18

Tables of means

Variate: B_mg_kg_2013_1st,B_mg_kg_2014_1st

Grand mean 22.66

Time	B_mg_kg_2013_1st	B_mg_kg_2014_1st					
	22.87	22.46					
Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	20.59	21.47	21.53	20.68	23.74	23.45	25.42
Boron	3.5kg/ha						
	24.43						

	Apply	soil	leaf				
		22.17	23.16				
	Time	Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha
B_mg_kg_2013_1st			20.38	21.59	22.12	20.50	24.00
B_mg_kg_2014_1st			20.81	21.34	20.93	20.86	23.49
	Time	Boron	2.5kg/ha	3kg/ha	3.5kg/ha		
B_mg_kg_2013_1st			23.13	25.75	25.49		
B_mg_kg_2014_1st			23.78	25.09	23.38		
	Time	Apply	soil	leaf			
B_mg_kg_2013_1st			22.45	23.29			
B_mg_kg_2014_1st			21.90	23.02			
	Boron	Apply	soil	leaf			
	0kg/ha		19.93	21.25			
	0.5kg/ha		20.68	22.25			
	1kg/ha		22.13	20.92			
	1.5kg/ha		19.69	21.67			
	2kg/ha		22.82	24.67			
	2.5kg/ha		24.04	22.86			
	3kg/ha		24.13	26.71			
	3.5kg/ha		23.97	24.90			
	Time	Boron	Apply	soil	leaf		
B_mg_kg_2013_1st		0kg/ha		19.42	21.34		
		0.5kg/ha		20.68	22.50		
		1kg/ha		23.25	21.00		
		1.5kg/ha		19.25	21.75		
		2kg/ha		23.00	25.00		
		2.5kg/ha		24.00	22.25		
		3kg/ha		24.25	27.25		
		3.5kg/ha		25.73	25.25		
B_mg_kg_2014_1st		0kg/ha		20.45	21.17		
		0.5kg/ha		20.67	22.01		
		1kg/ha		21.01	20.85		
		1.5kg/ha		20.13	21.59		
		2kg/ha		22.64	24.34		
		2.5kg/ha		24.09	23.48		
		3kg/ha		24.00	26.17		
		3.5kg/ha		22.21	24.55		

Least significant differences of means (5% level)

Table	Time	Boron	Apply	Time Boron
rep.	64	16	64	8
l.s.d.	0.686	2.725	1.363	3.025
d.f.	48	45	45	66.76
Except when comparing means with the same level(s) of Boron				1.941
d.f.				48

Table	Time Apply	Boron Apply	Time Boron Apply
rep.	32	8	4
l.s.d.	1.513	3.854	4.278

d.f.	66.76	45	66.76
Except when comparing means with the same level(s) of			
Apply	0.970		
d.f.	48		
Boron.Apply			2.745
d.f.			48

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: B_mg_kg_2013_1st,B_mg_kg_2014_1st

Stratum	d.f.	s.e.	cv%
rep	3	1.262	5.6
rep.Subject	45	2.706	11.9
rep.Subject.Time	48	1.931	8.5

Analysis of variance

Variate: B_mg_kg_2013_2nd,B_mg_kg_2014_2nd (220 DAS)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	3	44.25	14.75	0.89	
rep.Subject stratum					
Boron	7	716.94	102.42	6.16	<.001
Apply	1	230.85	230.85	13.89	<.001
Boron.Apply	7	210.85	30.12	1.81	0.108
Residual	45	747.93	16.62	1.26	
rep.Subject.Time stratum					
d.f. correction factor 1.0000					
Time	1	17.36	17.36	1.31	0.257
Time.Boron	7	64.81	9.26	0.70	0.671
Time.Apply	1	52.32	52.32	3.96	0.052
Time.Boron.Apply	7	129.29	18.47	1.40	0.228
Residual	48	633.75	13.20		
Total	127	2848.34			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 3 Subject 4	7.46	s.e. 2.42
rep 4 Subject 16	-6.19	s.e. 2.42

Tables of means

Variate: B_mg_kg_2013_2nd,B_mg_kg_2014_2nd

Grand mean 28.68

Time	B_mg_kg_2013_2nd	B_mg_kg_2014_2nd					
	28.31	29.05					
Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	23.31	26.84	29.02	29.15	29.38	29.77	30.98
Boron	3.5kg/ha						
	30.99						
Apply	soil	leaf					
	27.34	30.02					
Time	Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	
B_mg_kg_2013_2nd		23.37	26.42	28.37	27.62	29.01	
B_mg_kg_2014_2nd		23.25	27.27	29.67	30.68	29.75	
Time	Boron	2.5kg/ha	3kg/ha	3.5kg/ha			
B_mg_kg_2013_2nd		28.60	31.62	31.49			
B_mg_kg_2014_2nd		30.94	30.33	30.48			
Time	Apply	soil	leaf				
B_mg_kg_2013_2nd		26.33	30.29				
B_mg_kg_2014_2nd		28.35	29.75				
Boron	Apply	soil	leaf				
0kg/ha		23.35	23.28				
0.5kg/ha		27.48	26.20				
1kg/ha		27.95	30.09				
1.5kg/ha		27.26	31.05				
2kg/ha		25.44	33.33				
2.5kg/ha		28.56	30.98				
3kg/ha		29.36	32.60				
3.5kg/ha		29.30	32.67				
Time	Boron	Apply	soil	leaf			
B_mg_kg_2013_2nd	0kg/ha		23.62	23.12			
	0.5kg/ha		26.22	26.61			
	1kg/ha		27.30	29.44			
	1.5kg/ha		26.53	28.72			
	2kg/ha		25.15	32.87			
	2.5kg/ha		25.25	31.95			
	3kg/ha		28.67	34.58			
	3.5kg/ha		27.91	35.07			
B_mg_kg_2014_2nd	0kg/ha		23.07	23.43			
	0.5kg/ha		28.75	25.80			
	1kg/ha		28.60	30.74			
	1.5kg/ha		28.00	33.37			
	2kg/ha		25.72	33.78			
	2.5kg/ha		31.88	30.01			
	3kg/ha		30.04	30.62			
	3.5kg/ha		30.70	30.27			

Least significant differences of means (5% level)

Table	Time	Boron	Apply	Time Boron
rep.	64	16	64	8
l.s.d.	1.292	2.903	1.452	3.835
d.f.	48	45	45	91.03
Except when comparing means with the same level(s) of Boron				3.653
d.f.				48

Table	Time Apply	Boron Apply	Time Boron Apply
rep.	32	8	4
l.s.d.	1.918	4.106	5.424
d.f.	91.03	45	91.03
Except when comparing means with the same level(s) of Apply	1.826		
d.f.	48		
Boron.Apply			5.166
d.f.			48

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: B_mg_kg_2013_2nd,B_mg_kg_2014_2nd

Stratum	d.f.	s.e.	cv%
rep	3	0.679	2.4
rep.Subject	45	2.883	10.1
rep.Subject.Time	48	3.634	12.7

Appendix 5.5: Chapter 5 (B trial) root statistical analysis

Analysis of variance

Variate: B_mg_kg

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
rep stratum	3		3.1818	1.0606	2.27	
rep.*Units* stratum						
Boron	7		7.7187	1.1027	2.36	0.039
Lin	1		5.3166	5.3166	11.37	0.002
Quad	1		0.5451	0.5451	1.17	0.286
Deviations	5		1.8570	0.3714	0.79	0.560
Apply	1		0.2758	0.2758	0.59	0.447
Boron.Apply	7		9.7108	1.3873	2.97	0.012
Lin.Apply	1		1.1975	1.1975	2.56	0.117
Quad.Apply	1		1.5750	1.5750	3.37	0.073
Deviations	5		6.9384	1.3877	2.97	0.022
Residual	44	(1)	20.5784	0.4677		

Total 62 (1) 41.0381

Message: the following units have large residuals.

rep 2 *units* 3	1.432	s.e. 0.567
rep 4 *units* 8	-2.163	s.e. 0.567

Tables of means

Variate: B_mg_kg

Grand mean 8.474

Boron	0kg/ha	0.5kg/ha	1kg/ha	1.5kg/ha	2kg/ha	2.5kg/ha	3kg/ha
	7.701	8.498	8.230	8.581	8.427	8.765	8.820
Boron	3.5kg/ha						
	8.773						
Apply	soil	leaf					
	8.409	8.540					
Boron	Apply	soil	leaf				
0kg/ha		6.805	8.598				
0.5kg/ha		8.595	8.400				
1kg/ha		8.618	7.842				
1.5kg/ha		8.685	8.478				
2kg/ha		7.954	8.900				
2.5kg/ha		8.980	8.550				
3kg/ha		8.802	8.839				
3.5kg/ha		8.832	8.715				

Least significant differences of means (5% level)

Table	Boron	Apply	Boron Apply
rep.	8	32	4
d.f.	44	44	44
l.s.d.	0.6891	0.3446	0.9746

(Not adjusted for missing values)

Stratum standard errors and coefficients of variation

Variate: B_mg_kg

Stratum	d.f.	s.e.	cv%
rep	3	0.2575	3.0
rep.*Units*	44	0.6839	8.1

Appendix 6.1: Chapter 6 ((NH₄)₂SO₄ and dolomitic lime) yield statistical analysis

Analysis of variance

Variate: yield_2014

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	177.24	88.62	1.31	
rep.*Units* stratum					
L_t_ha	3	344.71	114.90	1.69	0.189
Lin	1	227.57	227.57	3.35	0.077
Quad	1	1.59	1.59	0.02	0.879
Deviations	1	115.54	115.54	1.70	0.202
N_kg_ha	3	156.33	52.11	0.77	0.521
Lin	1	54.14	54.14	0.80	0.379
Quad	1	98.55	98.55	1.45	0.237
Deviations	1	3.64	3.64	0.05	0.818
L_t_ha.N_kg_ha	9	461.13	51.24	0.76	0.657
Lin.Lin	1	71.66	71.66	1.06	0.312
Quad.Lin	1	116.30	116.30	1.71	0.200
Lin.Quad	1	7.26	7.26	0.11	0.746
Dev.Lin	1	71.62	71.62	1.06	0.312
Quad.Quad	1	69.31	69.31	1.02	0.320
Lin.Dev	1	26.90	26.90	0.40	0.534
Dev.Quad	1	1.48	1.48	0.02	0.883
Quad.Dev	1	18.02	18.02	0.27	0.610
Deviations	1	78.57	78.57	1.16	0.290
Residual	30	2035.02	67.83		
Total	47	3174.43			

Message: the following units have large residuals.

rep 2 *units* 13	-15.1	s.e. 6.5
rep 3 *units* 2	15.3	s.e. 6.5

Tables of means

Variate: yield_2014

Grand mean 33.8

L_t_ha	0	1	3	7	
	32.8	30.0	35.5	37.0	
N_kg_ha	0	60	120	200	
	33.8	32.5	32.2	36.8	
L_t_ha	N_kg_ha	0	60	120	200
0		36.6	35.8	29.0	29.8
1		29.0	25.7	30.4	34.8
3		34.7	34.6	29.8	43.1
7		35.0	33.9	39.6	39.4

Tables of means

Variate: yield_2015

Grand mean 42.4

L_t_ha	0	1	3	7	
	36.1	42.7	46.1	44.7	
N_kg_ha	0	60	120	200	
	37.6	44.2	42.8	44.9	
L_t_ha	N_kg_ha	0	60	120	200
0		26.1	44.5	37.5	36.3
1		35.4	42.0	47.7	45.8
3		44.4	48.9	39.1	51.9
7		44.4	41.6	46.9	45.8

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	5.91	5.91	11.83

Stratum standard errors and coefficients of variation

Variate: yield_2015

Stratum	d.f.	s.e.	cv%
rep	2	0.50	1.2
rep.*Units*	30	7.09	16.7

Analysis of variance

Variate: yield_2014,yield_2015

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	101.86	50.93	0.50	
rep.Subject stratum					
L_t_ha	3	746.41	248.80	2.44	0.084
Lin	1	536.01	536.01	5.25	0.029
Quad	1	200.14	200.14	1.96	0.172
Deviations	1	10.25	10.25	0.10	0.754
N_kg_ha	3	330.15	110.05	1.08	0.373
Lin	1	264.69	264.69	2.59	0.118
Quad	1	1.80	1.80	0.02	0.895
Deviations	1	63.66	63.66	0.62	0.436
L_t_ha.N_kg_ha	9	862.49	95.83	0.94	0.507
Lin.Lin	1	4.06	4.06	0.04	0.843
Quad.Lin	1	61.56	61.56	0.60	0.444
Lin.Quad	1	44.59	44.59	0.44	0.514
Dev.Lin	1	90.22	90.22	0.88	0.355
Quad.Quad	1	244.60	244.60	2.40	0.132
Lin.Dev	1	116.30	116.30	1.14	0.294
Deviations	3	301.15	100.38	0.98	0.414
Residual	30	3062.89	102.10	5.79	
rep.Subject.Time stratum					
d.f. correction factor 1.0000					
Time	1	1756.17	1756.17	99.61	<.001
Time.L_t_ha	3	300.09	100.03	5.67	0.003
Time.Lin	1	3.30	3.30	0.19	0.668
Time.Quad	1	152.80	152.80	8.67	0.006
Deviations	1	143.98	143.98	8.17	0.007
Time.N_kg_ha	3	223.53	74.51	4.23	0.013
Time.Lin	1	34.38	34.38	1.95	0.172
Time.Quad	1	161.27	161.27	9.15	0.005
Deviations	1	27.88	27.88	1.58	0.218
Time.L_t_ha.N_kg_ha	9	309.03	34.34	1.95	0.080
Time.Lin.Lin	1	99.15	99.15	5.62	0.024
Time.Quad.Lin	1	54.84	54.84	3.11	0.087
Time.Lin.Quad	1	109.99	109.99	6.24	0.018
Deviations	6	45.06	7.51	0.43	0.856
Residual	32	564.15	17.63		
Total	95	8256.76			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 13 Time yield_2014	-5.28	s.e. 2.42
rep 2 Subject 13 Time yield_2015	5.28	s.e. 2.42

rep 3 Subject 2 Time yield_2014	5.28	s.e. 2.42
rep 3 Subject 2 Time yield_2015	-5.28	s.e. 2.42

Tables of means

Variate: yield_2014,yield_2015

Grand mean 38.10

Time	yield_2014	yield_2015				
	33.82	42.38				
L_t_ha	0	1	3	7		
	34.45	36.35	40.80	40.82		
N_kg_ha	0	60	120	200		
	35.70	38.37	37.48	40.85		
Time	L_t_ha	0	1	3	7	
yield_2014		32.81	29.97	35.54	36.97	
yield_2015		36.08	42.72	46.06	44.66	
Time	N_kg_ha	0	60	120	200	
yield_2014		33.82	32.51	32.20	36.77	
yield_2015		37.58	44.23	42.77	44.93	
L_t_ha	N_kg_ha	0	60	120	200	
0		31.33	40.17	33.25	33.03	
1		32.23	33.85	39.02	40.28	
3		39.53	41.72	34.45	47.50	
7		39.72	37.75	43.22	42.58	
Time	L_t_ha	N_kg_ha	0	60	120	200
yield_2014	0		36.57	35.83	29.03	29.80
	1		29.03	25.73	30.37	34.77
	3		34.67	34.57	29.83	43.10
	7		35.03	33.90	39.57	39.40
yield_2015	0		26.10	44.50	37.47	36.27
	1		35.43	41.97	47.67	45.80
	3		44.40	48.87	39.07	51.90
	7		44.40	41.60	46.87	45.77

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
				L_t_ha
rep.	48	24	24	12
l.s.d.	1.746	5.957	5.957	6.383
d.f.	32	30	30	40.13
Except when comparing means with the same level(s) of				
L_t_ha				3.492
d.f.				32
Table	Time	L_t_ha	Time	
	N_kg_ha	N_kg_ha	L_t_ha	
			N_kg_ha	
rep.	12	6	3	

l.s.d.	6.383	11.914	12.766
d.f.	40.13	30	40.13
Except when comparing means with the same level(s) of			
N_kg_ha	3.492		
d.f.	32		
L_t_ha.N_kg_ha			6.983
d.f.			32

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: yield_2014,yield_2015

Stratum	d.f.	s.e.	cv%
rep	2	1.262	3.3
rep.Subject	30	7.145	18.8
rep.Subject.Time	32	4.199	11.0

Appendix 6.2: Chapter 6 ((NH₄)₂SO₄ and dolomitic lime) soil statistical analysis

Analysis of variance

Variate: Initial_Asat%,Acid_sat_%_post_harv_year1,Acid_sat_%_post_harv_year2 (0-15 cm depth, initial, post harvest 1 and post harvest 2)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	1056.43	528.22	5.57	
rep.Subject stratum					
L_t_ha	3	1258.08	419.36	4.42	0.011
N_kg_ha	3	1475.74	491.91	5.19	0.005
L_t_ha.N_kg_ha	9	1228.17	136.46	1.44	0.216
Residual	30	2843.57	94.79	3.67	
rep.Subject.Time stratum					
d.f. correction factor 0.8713					
Time	2	996.43	498.22	19.29	<.001
Time.L_t_ha	6	888.90	148.15	5.73	<.001
Time.N_kg_ha	6	594.40	99.07	3.83	0.004
Time.L_t_ha.N_kg_ha	18	496.26	27.57	1.07	0.406
Residual	64	1653.33	25.83		
Total	143	12491.33			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 1	-10.76	s.e. 4.44
rep 1 Subject 10	-9.65	s.e. 4.44
rep 2 Subject 16	-10.14	s.e. 4.44
rep 3 Subject 5	10.67	s.e. 4.44
rep 3 Subject 11	10.12	s.e. 4.44
rep 3 Subject 12	10.90	s.e. 4.44
rep 1 Subject 5 Time Initial_Asat%	-10.89	s.e. 3.39
rep 3 Subject 14 Time Initial_Asat%	13.11	s.e. 3.39
rep 3 Subject 14 Time Acid_sat_%_post_harv_year1	-8.22	s.e. 3.39

Tables of means

Variate: Initial_Asat%,Acid_sat_%_post_harv_year1,Acid_sat_%_post_harv_year2

Grand mean 9.84

Time	Initial_Asat%	Acid_sat_%_post_harv_year1				
	12.81	10.29				
Time	Acid_sat_%_post_harv_year2					
	6.42					
L_t_ha	0	1	3	7		
	14.14	10.42	8.86	5.94		
N_kg_ha	0	60	120	200		
	6.56	7.03	11.53	14.25		
Time	Initial_Asat%	L_t_ha	0	1	3	7
			13.00	12.33	13.00	12.92
Acid_sat_%_post_harv_year1			18.92	12.08	7.75	2.42
Acid_sat_%_post_harv_year2			10.50	6.83	5.83	2.50
Time	Initial_Asat%	N_kg_ha	0	60	120	200
			12.58	10.42	15.08	13.17
Acid_sat_%_post_harv_year1			4.25	6.42	12.17	18.33
Acid_sat_%_post_harv_year2			2.83	4.25	7.33	11.25
L_t_ha	N_kg_ha	0	60	120	200	
0		6.89	7.00	18.11	24.56	
1		9.22	9.44	11.00	12.00	
3		4.56	5.22	11.56	14.11	
7		5.56	6.44	5.44	6.33	
Time	Initial_Asat%	L_t_ha	N_kg_ha	0	60	
				11.00	8.67	
				17.00	10.33	
				9.33	7.67	
				13.00	15.00	
Acid_sat_%_post_harv_year1				6.00	7.33	
				7.00	10.67	
				2.33	5.67	

		7		1.67	2.00
Acid_sat_%_post_harv_year2		0		3.67	5.00
		1		3.67	7.33
		3		2.00	2.33
		7		2.00	2.33
	Time	L_t_ha	N_kg_ha	120	200
	Initial_Asat%	0		16.67	15.67
		1		13.00	9.00
		3		18.33	16.67
		7		12.33	11.33
Acid_sat_%_post_harv_year1		0		24.00	38.33
		1		13.33	17.33
		3		9.00	14.00
		7		2.33	3.67
Acid_sat_%_post_harv_year2		0		13.67	19.67
		1		6.67	9.67
		3		7.33	11.67
		7		1.67	4.00

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	36	36	12
l.s.d.	2.128	4.687	4.687	5.838
d.f.	55.76	30	30	61.75
Except when comparing means with the same level(s) of L_t_ha				4.256
d.f.				55.76

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	9	3
l.s.d.	5.838	9.373	11.676
d.f.	61.75	30	61.75
Except when comparing means with the same level(s) of N_kg_ha			
d.f.	4.256		
L_t_ha.N_kg_ha			8.511
d.f.	55.76		55.76

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Initial_Asat%,Acid_sat_%_post_harv_year1,Acid_sat_%_post_harv_year2

Stratum	d.f.	s.e.	cv%
rep	2	3.317	33.7
rep.Subject	30	5.621	57.1
rep.Subject.Time	64	5.083	51.7

Analysis of variance

Variate: Ca_mg_L,Ca_mg_L_3,Ca_mg_L_4,Ca_mg_L_5,Ca_mg_L_6 (15-30, 30-45, 45-60, 60-75, 75-90 cm depth samling)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	86859.	43429.	2.80	
rep.Subject stratum					
L_t_ha	3	503424.	167808.	10.81	<.001
N_kg_ha	3	59654.	19885.	1.28	0.299
L_t_ha.N_kg_ha	9	128508.	14279.	0.92	0.522
Residual	30	465578.	15519.	1.09	
rep.Subject.Time stratum					
d.f. correction factor 0.4848					
Time	4	828012.	207003.	14.50	<.001
Time.L_t_ha	12	117400.	9783.	0.69	0.658
Time.N_kg_ha	12	98898.	8242.	0.58	0.742
Time.L_t_ha.N_kg_ha	36	303354.	8427.	0.59	0.890
Residual	128	1827230.	14275.		
Total	239	4418916.			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 16	-125.4	s.e. 44.0
rep 1 Subject 7 Time Ca_mg_L_3	285.3	s.e. 87.3
rep 1 Subject 7 Time Ca_mg_L_5	-232.7	s.e. 87.3
rep 1 Subject 9 Time Ca_mg_L	252.1	s.e. 87.3
rep 3 Subject 16 Time Ca_mg_L_3	356.5	s.e. 87.3

Tables of means

Variate: Ca_mg_L,Ca_mg_L_3,Ca_mg_L_4,Ca_mg_L_5,Ca_mg_L_6

Grand mean 446.7

Time	Ca_mg_L	Ca_mg_L_3	Ca_mg_L_4	Ca_mg_L_5	Ca_mg_L_6
	409.0	488.2	514.6	469.5	352.0
L_t_ha	0	1	3	7	
	399.5	414.2	455.3	517.6	
N_kg_ha	0	60	120	200	
	434.6	452.0	430.0	469.9	

Time	L_t_ha	0	1	3	7
Ca_mg_L		358.3	396.2	400.0	481.6
Ca_mg_L_3		405.0	434.1	493.0	620.7
Ca_mg_L_4		480.0	476.9	520.5	581.0
Ca_mg_L_5		419.3	439.4	496.7	522.7
Ca_mg_L_6		335.1	324.2	366.2	382.3

Time	N_kg_ha	0	60	120	200
Ca_mg_L		423.8	428.5	401.2	382.6
Ca_mg_L_3		466.8	466.3	482.2	537.3
Ca_mg_L_4		518.2	496.2	494.0	550.0
Ca_mg_L_5		424.8	503.2	446.3	503.8
Ca_mg_L_6		339.7	365.9	326.2	376.1

L_t_ha	N_kg_ha	0	60	120	200
0		403.8	387.0	428.1	379.2
1		393.5	417.7	389.5	455.9
3		442.8	441.9	434.2	502.1
7		498.5	561.5	468.1	542.5

Time	L_t_ha	N_kg_ha	0	60	120	200
Ca_mg_L	0		398.3	418.7	324.7	291.3
	1		375.7	376.3	392.0	440.7
	3		485.7	398.0	364.0	352.3
	7		435.3	521.0	524.0	446.0
Ca_mg_L_3	0		439.7	379.0	466.3	335.0
	1		359.0	375.0	439.3	563.0
	3		505.0	443.7	447.0	576.3
	7		563.7	667.7	576.3	675.0
Ca_mg_L_4	0		443.3	473.0	514.7	489.0
	1		478.3	489.7	461.3	478.3
	3		539.3	470.0	507.7	565.0
	7		611.7	552.3	492.3	667.7
Ca_mg_L_5	0		391.0	395.3	471.7	419.3
	1		395.3	491.3	390.3	480.7
	3		420.0	524.7	481.0	561.0
	7		492.7	601.7	442.3	554.0
Ca_mg_L_6	0		346.7	269.0	363.3	361.3
	1		359.0	356.3	264.7	317.0
	3		264.0	373.3	371.3	456.0
	7		389.0	465.0	305.3	370.0

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
rep.	48	60	60	L_t_ha 12
l.s.d.	54.76	46.45	46.45	109.97
d.f.	62.06	30	30	87.07
Except when comparing means with the same level(s) of L_t_ha				109.52
d.f.				62.06

Table	Time	L_t_ha	Time
rep.	12	15	N_kg_ha 3
l.s.d.	109.97	92.90	219.94
d.f.	87.07	30	87.07

Except when comparing means with the same level(s) of

N_kg_ha	109.52	
d.f.	62.06	
L_t_ha.N_kg_ha		219.04
d.f.		62.06

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Ca_mg_L,Ca_mg_L_3,Ca_mg_L_4,Ca_mg_L_5,Ca_mg_L_6

Stratum	d.f.	s.e.	cv%
rep	2	23.30	5.2
rep.Subject	30	55.71	12.5
rep.Subject.Time	128	119.48	26.7

Analysis of variance

Variate: Ca_mg_L_2,Ca_mg_L_1,Ca_mg_L (0-15 cm depth, initial, post harvest 1 and post harvest 2)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	234486.	117243.	4.53	
rep.Subject stratum					
L_t_ha	3	319872.	106624.	4.12	0.015
N_kg_ha	3	49153.	16384.	0.63	0.600
L_t_ha.N_kg_ha	9	206019.	22891.	0.88	0.550
Residual	30	776794.	25893.	4.72	
rep.Subject.Time stratum					
d.f. correction factor 0.8257					
Time	2	556129.	278065.	50.64	<.001
Time.L_t_ha	6	360451.	60075.	10.94	<.001
Time.N_kg_ha	6	49632.	8272.	1.51	0.204
Time.L_t_ha.N_kg_ha	18	48017.	2668.	0.49	0.937
Residual	64	351430.	5491.		
Total	143	2951984.			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 16	161.4	s.e. 73.4
rep 1 Subject 14 Time Ca_mg_L_2	119.9	s.e. 49.4
rep 3 Subject 15 Time Ca_mg_L_1	128.6	s.e. 49.4
rep 3 Subject 16 Time Ca_mg_L_1	139.7	s.e. 49.4

Tables of means

Variate: Ca_mg_L_2,Ca_mg_L_1,Ca_mg_L

Grand mean 423.8

Time	Ca_mg_L_2	Ca_mg_L_1	Ca_mg_L			
	356.1	506.2	409.0			
L_t_ha	0	1	3	7		
	369.8	393.7	438.0	493.5		
N_kg_ha	0	60	120	200		
	427.9	450.1	398.8	418.2		
Time	L_t_ha	0	1	3	7	
Ca_mg_L_2		360.9	362.6	368.7	332.2	
Ca_mg_L_1		390.2	422.3	545.2	666.8	
Ca_mg_L		358.2	396.2	400.0	481.6	
Time	N_kg_ha	0	60	120	200	
Ca_mg_L_2		340.8	367.3	326.5	389.9	
Ca_mg_L_1		519.2	554.6	468.8	482.1	
Ca_mg_L		423.8	428.5	401.2	382.6	
L_t_ha	N_kg_ha	0	60	120	200	
0		405.9	429.1	327.4	316.8	
1		350.9	384.2	387.6	452.1	
3		508.3	462.6	380.6	400.6	
7		446.6	524.6	499.7	503.3	
Time	L_t_ha	N_kg_ha	0	60	120	200
Ca_mg_L_2	0		361.0	376.7	318.0	388.0
	1		294.7	356.7	351.3	447.7
	3		414.7	412.0	291.3	357.0
	7		292.7	323.7	345.3	367.0
Ca_mg_L_1	0		458.3	492.0	339.7	271.0
	1		382.3	419.7	419.3	468.0
	3		624.7	577.7	486.3	492.3
	7		611.7	729.0	629.7	697.0
Ca_mg_L	0		398.3	418.7	324.7	291.3
	1		375.7	376.3	392.0	440.7
	3		485.7	398.0	364.0	352.3
	7		435.3	521.0	524.0	446.0

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
				L_t_ha
rep.	48	36	36	12
l.s.d.	31.34	77.46	77.46	93.69
d.f.	52.84	30	30	55.21
Except when comparing means with the same level(s) of L_t_ha				62.68
d.f.				52.84

Table	Time	L_t_ha	Time
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	N_kg_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	9	3
l.s.d.	93.69	154.92	187.39
d.f.	55.21	30	55.21
Except when comparing means with the same level(s) of			
N_kg_ha	62.68		
d.f.	52.84		
L_t_ha.N_kg_ha			125.36
d.f.			52.84

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Ca_mg_L_2,Ca_mg_L_1,Ca_mg_L

Stratum	d.f.	s.e.	cv%
rep	2	49.42	11.7
rep.Subject	30	92.90	21.9
rep.Subject.Time	64	74.10	17.5

Analysis of variance

Variate: Mg_mg_L,Mg_mg_L_3,Mg_mg_L_4,Mg_mg_L_5,Mg_mg_L_6 (15-30, 30-45, 45-60, 60-75, 75-90 cm depth samling)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	2186.	1093.	0.50	
rep.Subject stratum					
L_t_ha	3	4202.	1401.	0.64	0.595
N_kg_ha	3	7888.	2629.	1.20	0.326
L_t_ha.N_kg_ha	9	10983.	1220.	0.56	0.820
Residual	30	65625.	2187.	1.56	
rep.Subject.Time stratum					
d.f. correction factor 0.6296					
Time	4	728454.	182114.	129.64	<.001
Time.L_t_ha	12	8602.	717.	0.51	0.836
Time.N_kg_ha	12	18163.	1514.	1.08	0.387
Time.L_t_ha.N_kg_ha	36	46364.	1288.	0.92	0.576
Residual	128	179810.	1405.		
Total	239	1072277.			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Message: the following units have large residuals.

rep 3 Subject 14	35.3	s.e. 16.5
rep 1 Subject 7 Time Mg_mg_L_3	78.8	s.e. 27.4
rep 1 Subject 7 Time Mg_mg_L_6	-78.9	s.e. 27.4
rep 3 Subject 14 Time Mg_mg_L_6	83.0	s.e. 27.4

Tables of means

Variate: Mg_mg_L,Mg_mg_L_3,Mg_mg_L_4,Mg_mg_L_5,Mg_mg_L_6

Grand mean 164.2

Time	Mg_mg_L	Mg_mg_L_3	Mg_mg_L_4	Mg_mg_L_5	Mg_mg_L_6	
	90.5	114.6	168.6	214.3	233.2	
	L_t_ha	0	1	3	7	
		158.4	166.5	162.5	169.5	
	N_kg_ha	0	60	120	200	
		159.8	170.7	157.4	169.1	
Time	L_t_ha	0	1	3	7	
Mg_mg_L		86.5	92.1	87.4	95.9	
Mg_mg_L_3		98.3	108.5	119.3	132.4	
Mg_mg_L_4		166.1	167.8	166.5	174.1	
Mg_mg_L_5		207.2	219.3	216.3	214.2	
Mg_mg_L_6		234.1	244.8	222.8	231.1	
Time	N_kg_ha	0	60	120	200	
Mg_mg_L		96.5	92.1	90.0	83.3	
Mg_mg_L_3		115.8	109.3	110.8	122.8	
Mg_mg_L_4		175.1	165.8	159.8	173.8	
Mg_mg_L_5		195.8	232.5	202.3	226.5	
Mg_mg_L_6		215.7	253.8	224.2	239.1	
	L_t_ha	N_kg_ha	0	60	120	200
	0		146.4	172.1	158.7	156.5
	1		162.9	170.0	158.1	174.9
	3		154.5	160.6	154.1	180.7
	7		175.2	180.0	158.7	164.3
Time	L_t_ha	N_kg_ha	0	60	120	200
Mg_mg_L	0		85.3	92.7	92.3	75.7
	1		94.3	84.7	93.3	96.0
	3		106.0	94.3	79.0	70.3
	7		100.3	96.7	95.3	91.3
Mg_mg_L_3	0		112.0	88.7	106.7	86.0
	1		87.7	87.7	114.0	144.7
	3		129.3	112.0	101.7	134.3
	7		134.0	148.7	121.0	126.0
Mg_mg_L_4	0		160.3	185.3	157.0	161.7
	1		174.0	173.3	154.3	169.3
	3		178.7	145.3	166.0	176.0
	7		187.3	159.0	162.0	188.0
Mg_mg_L_5	0		170.0	233.3	219.3	206.0
	1		196.3	254.3	184.7	242.0
	3		197.3	211.7	215.7	240.7
	7		219.3	230.7	189.7	217.3
Mg_mg_L_6	0		204.3	260.7	218.3	253.0
	1		262.3	250.0	244.3	222.3
	3		161.0	239.7	208.3	282.3
	7		235.0	265.0	225.7	198.7

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	60	60	12
l.s.d.	16.45	17.44	17.44	34.56
d.f.	80.59	30	30	110.55
Except when comparing means with the same level(s) of L_t_ha				32.90
d.f.				80.59

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	15	3
l.s.d.	34.56	34.88	69.13
d.f.	110.55	30	110.55
Except when comparing means with the same level(s) of N_kg_ha			
d.f.	32.90		
L_t_ha.N_kg_ha			65.80
d.f.	80.59		80.59

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Mg_mg_L,Mg_mg_L_3,Mg_mg_L_4,Mg_mg_L_5,Mg_mg_L_6

Stratum	d.f.	s.e.	cv%
rep	2	3.70	2.3
rep.Subject	30	20.92	12.7
rep.Subject.Time	128	37.48	22.8

Analysis of variance

Variate: Mg_mg_L_2,Mg_mg_L_1,Mg_mg_L (0-15 cm depth, initial, post harvest 1 and post harvest 2)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	16236.4	8118.2	7.04	
rep.Subject stratum					
L_t_ha	3	6200.0	2066.7	1.79	0.170
N_kg_ha	3	4066.3	1355.4	1.18	0.335
L_t_ha.N_kg_ha	9	7806.6	867.4	0.75	0.659
Residual	30	34576.7	1152.6	3.94	
rep.Subject.Time stratum					
d.f. correction factor 0.9567					
Time	2	8593.3	4296.7	14.67	<.001
Time.L_t_ha	6	14180.9	2363.5	8.07	<.001
Time.N_kg_ha	6	6485.3	1080.9	3.69	0.004
Time.L_t_ha.N_kg_ha	18	2524.2	140.2	0.48	0.954
Residual	64	18740.2	292.8		
Total	143	119410.0			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Message: the following units have large residuals.

rep 1 Subject 1	33.4	s.e. 15.5
rep 2 Subject 16	39.6	s.e. 15.5
rep 2 Subject 13 Time Mg_mg_L_2	30.1	s.e. 11.4

Tables of means

Variate: Mg_mg_L_2, Mg_mg_L_1, Mg_mg_L

Grand mean 97.4

	Time	Mg_mg_L_2	Mg_mg_L_1	Mg_mg_L			
		93.5	108.2	90.5			
	L_t_ha	0	1	3	7		
		89.7	95.1	97.0	107.8		
	N_kg_ha	0	60	120	200		
		103.2	102.1	91.3	92.9		
	Time	L_t_ha	0	1	3	7	
Mg_mg_L_2			95.2	97.4	93.8	87.6	
Mg_mg_L_1			87.3	95.9	109.8	139.8	
Mg_mg_L			86.5	92.1	87.4	95.9	
	Time	N_kg_ha	0	60	120	200	
Mg_mg_L_2			91.2	94.2	86.8	101.9	
Mg_mg_L_1			121.8	120.2	97.2	93.5	
Mg_mg_L			96.5	92.1	90.0	83.3	
	L_t_ha	N_kg_ha	0	60	120	200	
	0		95.4	101.0	85.3	76.9	
	1		92.6	92.4	92.3	103.2	
	3		117.8	103.8	83.4	82.9	
	7		106.9	111.3	104.1	108.7	
	Time	L_t_ha	N_kg_ha	0	60	120	200
Mg_mg_L_2		0		95.7	97.0	85.3	103.0
		1		83.0	95.7	92.3	118.7
		3		107.3	99.7	79.7	88.3
		7		78.7	84.3	89.7	97.7
Mg_mg_L_1		0		105.3	113.3	78.3	52.0
		1		100.3	97.0	91.3	95.0
		3		140.0	117.3	91.7	90.0
		7		141.7	153.0	127.3	137.0
Mg_mg_L		0		85.3	92.7	92.3	75.7
		1		94.3	84.7	93.3	96.0
		3		106.0	94.3	79.0	70.3
		7		100.3	96.7	95.3	91.3

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	36	36	12
l.s.d.	7.04	16.34	16.34	19.80
d.f.	61.23	30	30	60.57
Except when comparing means with the same level(s) of L_t_ha				14.07
d.f.				61.23

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	9	3
l.s.d.	19.80	32.68	39.61
d.f.	60.57	30	60.57
Except when comparing means with the same level(s) of N_kg_ha			
d.f.	14.07		
L_t_ha.N_kg_ha			28.15
d.f.	61.23		61.23

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Mg_mg_L_2,Mg_mg_L_1,Mg_mg_L

Stratum	d.f.	s.e.	cv%
rep	2	13.00	13.4
rep.Subject	30	19.60	20.1
rep.Subject.Time	64	17.11	17.6

Analysis of variance

Variate: PH_KCL_2,PH_KCL_1,PH_KCL (0-15 cm depth, initial, post harvest 1 and post harvest 2)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.88612	0.44306	2.36	
rep.Subject stratum					
L_t_ha	3	6.15669	2.05223	10.95	<.001
N_kg_ha	3	4.40977	1.46992	7.84	<.001
L_t_ha.N_kg_ha	9	1.06640	0.11849	0.63	0.761
Residual	30	5.62351	0.18745	2.97	
rep.Subject.Time stratum					
d.f. correction factor 0.9796					
Time	2	1.90532	0.95266	15.09	<.001
Time.L_t_ha	6	4.14838	0.69140	10.95	<.001
Time.N_kg_ha	6	2.89119	0.48187	7.63	<.001
Time.L_t_ha.N_kg_ha	18	0.56493	0.03138	0.50	0.948
Residual	64	4.04044	0.06313		
Total	143	31.69274			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 14	-0.517	s.e. 0.198
rep 1 Subject 14 Time PH_KCL_2	0.439	s.e. 0.168
rep 3 Subject 2 Time PH_KCL_2	-0.444	s.e. 0.168

Tables of means

Variate: PH_KCL_2,PH_KCL_1,PH_KCL

Grand mean 4.328

	Time PH_KCL_2	PH_KCL_1	PH_KCL			
	4.185	4.332	4.466			
	L_t_ha	0	1	3	7	
		4.144	4.186	4.311	4.670	
	N_kg_ha	0	60	120	200	
		4.521	4.471	4.222	4.097	
Time	L_t_ha	0	1	3	7	
PH_KCL_2		4.184	4.223	4.188	4.145	
PH_KCL_1		3.981	4.072	4.327	4.948	
PH_KCL		4.267	4.265	4.418	4.916	
Time	N_kg_ha	0	60	120	200	
PH_KCL_2		4.128	4.219	4.167	4.226	
PH_KCL_1		4.624	4.513	4.178	4.012	
PH_KCL		4.812	4.680	4.320	4.053	
	L_t_ha	N_kg_ha	0	60	120	200
	0		4.334	4.429	3.963	3.849
	1		4.328	4.147	4.200	4.071
	3		4.540	4.549	4.118	4.037
	7		4.883	4.759	4.606	4.431
Time	L_t_ha	N_kg_ha	0	60	120	200
PH_KCL_2	0		4.153	4.257	4.113	4.213
	1		4.030	4.197	4.303	4.360
	3		4.213	4.337	4.083	4.117
	7		4.113	4.087	4.167	4.213
PH_KCL_1	0		4.217	4.353	3.820	3.533
	1		4.273	4.097	4.027	3.890
	3		4.747	4.473	4.097	3.990
	7		5.260	5.130	4.770	4.633
PH_KCL	0		4.633	4.677	3.957	3.800
	1		4.680	4.147	4.270	3.963
	3		4.660	4.837	4.173	4.003
	7		5.277	5.060	4.880	4.447

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	36	36	12
l.s.d.	0.1029	0.2084	0.2084	0.2643
d.f.	62.69	30	30	69.04
Except when comparing means with the same level(s) of L_t_ha				0.2057
d.f.				62.69

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	9	3
l.s.d.	0.2643	0.4168	0.5286
d.f.	69.04	30	69.04
Except when comparing means with the same level(s) of N_kg_ha			
d.f.	0.2057		
L_t_ha.N_kg_ha			0.4115
d.f.	62.69		62.69

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: PH_KCL_2,PH_KCL_1,PH_KCL

Stratum	d.f.	s.e.	cv%
rep	2	0.0961	2.2
rep.Subject	30	0.2500	5.8
rep.Subject.Time	64	0.2513	5.8

Analysis of variance

Variate: PH_KCL,PH_KCL_3,PH_KCL_4,PH_KCL_5,PH_KCL_6 (15-30, 30-45, 45-60, 60-75, 75-90 cm depth samling)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	4.2371	2.1185	7.62	
rep.Subject stratum					
L_t_ha	3	11.3143	3.7714	13.57	<.001
N_kg_ha	3	3.2708	1.0903	3.92	0.018
L_t_ha.N_kg_ha	9	2.8447	0.3161	1.14	0.368
Residual	30	8.3361	0.2779	2.28	
rep.Subject.Time stratum					
d.f. correction factor 0.4300					
Time	4	1.4079	0.3520	2.89	0.071
Time.L_t_ha	12	6.8697	0.5725	4.70	0.001
Time.N_kg_ha	12	2.1921	0.1827	1.50	0.203
Time.L_t_ha.N_kg_ha	36	3.8946	0.1082	0.89	0.582
Residual	128	15.5761	0.1217		
Total	239	59.9434			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Message: the following units have large residuals.

rep 2 Subject 7	-0.453	s.e. 0.186
rep 3 Subject 16	0.613	s.e. 0.186
rep 1 Subject 7 Time PH_KCL_3	0.690	s.e. 0.255
rep 1 Subject 16 Time PH_KCL_3	-0.745	s.e. 0.255
rep 2 Subject 4 Time PH_KCL_3	0.734	s.e. 0.255
rep 3 Subject 16 Time PH_KCL_3	1.357	s.e. 0.255
rep 3 Subject 16 Time PH_KCL_5	-0.839	s.e. 0.255
rep 3 Subject 16 Time PH_KCL_6	-0.733	s.e. 0.255

Tables of means

Variate: PH_KCL,PH_KCL_3,PH_KCL_4,PH_KCL_5,PH_KCL_6

Grand mean 4.556

Time	PH_KCL	PH_KCL_3	PH_KCL_4	PH_KCL_5	PH_KCL_6	
	4.466	4.537	4.498	4.594	4.683	
L_t_ha	0	1	3	7		
	4.348	4.395	4.580	4.901		
N_kg_ha	0	60	120	200		
	4.698	4.627	4.505	4.393		
Time	L_t_ha	0	1	3	7	
PH_KCL		4.267	4.265	4.418	4.916	
PH_KCL_3		4.154	4.178	4.453	5.364	
PH_KCL_4		4.324	4.325	4.504	4.840	
PH_KCL_5		4.407	4.563	4.713	4.693	
PH_KCL_6		4.587	4.646	4.810	4.691	
Time	N_kg_ha	0	60	120	200	
PH_KCL		4.812	4.680	4.320	4.053	
PH_KCL_3		4.630	4.619	4.518	4.383	
PH_KCL_4		4.590	4.498	4.472	4.433	
PH_KCL_5		4.727	4.638	4.518	4.493	
PH_KCL_6		4.732	4.702	4.696	4.603	
L_t_ha	N_kg_ha	0	60	120	200	
0		4.543	4.471	4.270	4.107	
1		4.592	4.373	4.365	4.251	
3		4.725	4.471	4.493	4.629	
7		4.933	5.194	4.890	4.586	
Time	L_t_ha	N_kg_ha	0	60	120	200
PH_KCL	0		4.633	4.677	3.957	3.800
	1		4.680	4.147	4.270	3.963
	3		4.660	4.837	4.173	4.003
	7		5.277	5.060	4.880	4.447
PH_KCL_3	0		4.463	4.300	4.040	3.813
	1		4.317	4.033	4.293	4.070
	3		4.730	4.183	4.197	4.700
	7		5.010	5.960	5.540	4.947
PH_KCL_4	0		4.583	4.280	4.293	4.140

	1	4.413	4.430	4.290	4.167
	3	4.643	4.183	4.470	4.720
	7	4.720	5.100	4.833	4.707
PH_KCL_5	0	4.527	4.487	4.383	4.230
	1	4.743	4.670	4.353	4.483
	3	4.837	4.490	4.700	4.827
	7	4.800	4.903	4.633	4.433
PH_KCL_6	0	4.510	4.610	4.677	4.550
	1	4.807	4.587	4.620	4.570
	3	4.757	4.663	4.923	4.897
	7	4.857	4.947	4.563	4.397

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	60	60	12
l.s.d.	0.1629	0.1966	0.1966	0.3629
d.f.	55.05	30	30	85.00
Except when comparing means with the same level(s) of L_t_ha				0.3257
d.f.				55.05

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	15	3
l.s.d.	0.3629	0.3931	0.7258
d.f.	85.00	30	85.00
Except when comparing means with the same level(s) of N_kg_ha			0.3257
d.f.	55.05		
L_t_ha.N_kg_ha			0.6514
d.f.			55.05

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: PH_KCL,PH_KCL_3,PH_KCL_4,PH_KCL_5,PH_KCL_6

Stratum	d.f.	s.e.	cv%
rep	2	0.1627	3.6
rep.Subject	30	0.2357	5.2
rep.Subject.Time	128	0.3488	7.7

Analysis of variance

Variate: Acidity_cmol_L_2,Acidity_cmol_L_1,Acidity_cmol_L (0-15 cm depth, initial, post harvest 1 and post harvest 2)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.52364	0.26182	3.94	

rep.Subject stratum					
L_t_ha	3	0.99229	0.33076	4.98	0.006
N_kg_ha	3	1.39112	0.46371	6.99	0.001
L_t_ha.N_kg_ha	9	0.81100	0.09011	1.36	0.251
Residual	30	1.99133	0.06638	3.43	
rep.Subject.Time stratum					
d.f. correction factor 0.8505					
Time	2	0.76142	0.38071	19.65	<.001
Time.L_t_ha	6	0.68027	0.11338	5.85	<.001
Time.N_kg_ha	6	0.64064	0.10677	5.51	<.001
Time.L_t_ha.N_kg_ha	18	0.32845	0.01825	0.94	0.527
Residual	64	1.24009	0.01938		
Total	143	9.36025			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 10	-0.281	s.e. 0.118
rep 2 Subject 16	-0.306	s.e. 0.118
rep 3 Subject 5	0.312	s.e. 0.118
rep 3 Subject 12	0.300	s.e. 0.118
rep 1 Subject 5 Time Acidity_cmol_L_2	-0.364	s.e. 0.093
rep 1 Subject 5 Time Acidity_cmol_L_1	0.269	s.e. 0.093
rep 3 Subject 14 Time Acidity_cmol_L_2	0.376	s.e. 0.093
rep 3 Subject 14 Time Acidity_cmol_L_1	-0.281	s.e. 0.093

Tables of means

Variate: Acidity_cmol_L_2,Acidity_cmol_L_1,Acidity_cmol_L

Grand mean 0.311

Time	Acidity_cmol_L_2 0.379	Acidity_cmol_L_1 0.345	Acidity_cmol_L 0.210
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L_t_ha	0 0.424	1 0.334	3 0.293	7 0.193
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N_kg_ha	0 0.211	60 0.231	120 0.348	200 0.456
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Time	L_t_ha	0	1	3	7
Acidity_cmol_L_2		0.381	0.366	0.388	0.381
Acidity_cmol_L_1		0.568	0.403	0.296	0.111
Acidity_cmol_L		0.324	0.233	0.196	0.088

Time	N_kg_ha	0	60	120	200
Acidity_cmol_L_2		0.383	0.321	0.423	0.389
Acidity_cmol_L_1		0.158	0.229	0.383	0.609

Acidity_cmol_L			0.093	0.142	0.238	0.368
L_t_ha	N_kg_ha		0	60	120	200
0			0.228	0.230	0.543	0.697
1			0.277	0.317	0.316	0.428
3			0.176	0.171	0.351	0.476
7			0.166	0.204	0.181	0.222
Time	L_t_ha	N_kg_ha		0	60	120
Acidity_cmol_L_2	0			0.340	0.277	0.483
	1			0.493	0.330	0.337
	3			0.343	0.237	0.497
	7			0.357	0.440	0.373
Acidity_cmol_L_1	0			0.220	0.260	0.700
	1			0.227	0.363	0.413
	3			0.110	0.200	0.310
	7			0.073	0.093	0.107
Acidity_cmol_L	0			0.123	0.153	0.447
	1			0.110	0.257	0.197
	3			0.073	0.077	0.247
	7			0.067	0.080	0.063
Time	L_t_ha	N_kg_ha		200		
Acidity_cmol_L_2	0			0.423		
	1			0.303		
	3			0.477		
	7			0.353		
Acidity_cmol_L_1	0			1.093		
	1			0.610		
	3			0.563		
	7			0.170		
Acidity_cmol_L	0			0.573		
	1			0.370		
	3			0.387		
	7			0.143		

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
				L_t_ha
rep.	48	36	36	12
l.s.d.	0.0585	0.1240	0.1240	0.1570
d.f.	54.43	30	30	63.35
Except when comparing means with the same level(s) of L_t_ha				0.1171
d.f.				54.43

Table	Time	L_t_ha	Time
	N_kg_ha	N_kg_ha	L_t_ha
			N_kg_ha
rep.	12	9	3
l.s.d.	0.1570	0.2480	0.3140
d.f.	63.35	30	63.35
Except when comparing means with the same level(s) of N_kg_ha			0.1171
d.f.	54.43		
L_t_ha.N_kg_ha			0.2342
d.f.			54.43

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Acidity_cmol_L_2,Acidity_cmol_L_1,Acidity_cmol_L

Stratum	d.f.	s.e.	cv%
rep	2	0.0739	23.7
rep.Subject	30	0.1487	47.8
rep.Subject.Time	64	0.1392	44.7

Analysis of variance

Variate: Acidity_cmol_L,Acidity_cmol_L_3,Acidity_cmol_L_4,Acidity_cmol_L_5,Acidity_cmol_L_6 (15-30, 30-45, 45-60, 60-75, 75-90 cm depth samling)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.89762	0.44881	10.84	
rep.Subject stratum					
L_t_ha	3	0.69521	0.23174	5.60	0.004
N_kg_ha	3	1.04067	0.34689	8.38	<.001
L_t_ha.N_kg_ha	9	0.77486	0.08610	2.08	0.064
Residual	30	1.24166	0.04139	1.89	
rep.Subject.Time stratum					
d.f. correction factor 0.5103					
Time	4	0.13330	0.03333	1.52	0.226
Time.L_t_ha	12	0.27451	0.02288	1.04	0.406
Time.N_kg_ha	12	0.57011	0.04751	2.17	0.056
Time.L_t_ha.N_kg_ha	36	1.10527	0.03070	1.40	0.160
Residual	128	2.80372	0.02190		
Total	239	9.53694			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 9	0.2517	s.e. 0.0719
rep 3 Subject 10	-0.1861	s.e. 0.0719
rep 1 Subject 7 Time Acidity_cmol_L_3	-0.3033	s.e. 0.1081
rep 1 Subject 9 Time Acidity_cmol_L	-0.4087	s.e. 0.1081
rep 1 Subject 9 Time Acidity_cmol_L_5	0.4380	s.e. 0.1081
rep 2 Subject 16 Time Acidity_cmol_L_3	-0.3573	s.e. 0.1081
rep 3 Subject 5 Time Acidity_cmol_L	0.2940	s.e. 0.1081

Tables of means

Variate: Acidity_cmol_L,Acidity_cmol_L_3,Acidity_cmol_L_4,Acidity_cmol_L_5,Acidity_cmol_L_6

Grand mean 0.2260

Time	Acidity_cmol_L	Acidity_cmol_L_3	Acidity_cmol_L_4	Acidity_cmol_L_5	
	0.2104	0.2673	0.2277	0.2275	
Time	Acidity_cmol_L_6				
	0.1973				
L_t_ha	0	1	3	7	
	0.2688	0.2860	0.1957	0.1537	
N_kg_ha	0	60	120	200	
	0.1450	0.1843	0.2600	0.3148	
Time	L_t_ha	0	1	3	7
Acidity_cmol_L		0.3242	0.2333	0.1958	0.0883
Acidity_cmol_L_3		0.3633	0.3250	0.2158	0.1650
Acidity_cmol_L_4		0.2267	0.3117	0.1967	0.1758
Acidity_cmol_L_5		0.2392	0.3108	0.1958	0.1642
Acidity_cmol_L_6		0.1908	0.2492	0.1742	0.1750
Time	N_kg_ha	0	60	120	200
Acidity_cmol_L		0.0933	0.1417	0.2383	0.3683
Acidity_cmol_L_3		0.1383	0.2383	0.2292	0.4633
Acidity_cmol_L_4		0.1483	0.1975	0.2667	0.2983
Acidity_cmol_L_5		0.1800	0.1675	0.3258	0.2367
Acidity_cmol_L_6		0.1650	0.1767	0.2400	0.2075
L_t_ha	N_kg_ha	0	60	120	200
0		0.1647	0.1633	0.2800	0.4673
1		0.1593	0.2367	0.3780	0.3700
3		0.1533	0.2560	0.2087	0.1647
7		0.1027	0.0813	0.1733	0.2573
Time	L_t_ha	N_kg_ha	0	60	120
Acidity_cmol_L	0		0.1233	0.1533	0.4467
	1		0.1100	0.2567	0.1967
	3		0.0733	0.0767	0.2467
	7		0.0667	0.0800	0.0633
Acidity_cmol_L_3	0		0.1667	0.1667	0.3133
	1		0.1867	0.3533	0.2167
	3		0.1033	0.3633	0.2767
	7		0.0967	0.0700	0.1100
Acidity_cmol_L_4	0		0.1233	0.1800	0.2200
	1		0.1733	0.1967	0.4367
	3		0.1700	0.3367	0.1833
	7		0.1267	0.0767	0.2267
Acidity_cmol_L_5	0		0.2133	0.1633	0.2267
	1		0.1967	0.1367	0.6600
	3		0.2167	0.2667	0.1767
	7		0.0933	0.1033	0.2400
Acidity_cmol_L_6	0		0.1967	0.1533	0.1933
	1		0.1300	0.2400	0.3800
	3		0.2033	0.2367	0.1600

	7	0.1300	0.0767	0.2267
Time	L_t_ha	N_kg_ha	200	
Acidity_cmol_L	0	0.5733		
	1	0.3700		
	3	0.3867		
	7	0.1433		
Acidity_cmol_L_3	0	0.8067		
	1	0.5433		
	3	0.1200		
	7	0.3833		
Acidity_cmol_L_4	0	0.3833		
	1	0.4400		
	3	0.0967		
	7	0.2733		
Acidity_cmol_L_5	0	0.3533		
	1	0.2500		
	3	0.1233		
	7	0.2200		
Acidity_cmol_L_6	0	0.2200		
	1	0.2467		
	3	0.0967		
	7	0.2667		

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	60	60	12
l.s.d.	0.06728	0.07586	0.07586	0.14534
d.f.	65.32	30	30	95.31
Except when comparing means with the same level(s) of L_t_ha				0.13456
d.f.				65.32

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	15	3
l.s.d.	0.14534	0.15171	0.29067
d.f.	95.31	30	95.31
Except when comparing means with the same level(s) of N_kg_ha			
d.f.	0.13456		
L_t_ha.N_kg_ha	65.32		0.26912
d.f.			65.32

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Acidity_cmol_L,Acidity_cmol_L_3,Acidity_cmol_L_4,Acidity_cmol_L_5,Acidity_cmol_L_6

Stratum	d.f.	s.e.	cv%
rep	2	0.07490	33.1
rep.Subject	30	0.09098	40.3
rep.Subject.Time	128	0.14800	65.5

Analysis of variance

Variate: ASAT_%,ASAT_%_3,ASAT_%_4,ASAT_%_5,ASAT_%_6 (15-30, 30-45, 45-60, 60-75, 75-90 cm depth samling)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	497.41	248.70	7.81	
rep.Subject stratum					
L_t_ha	3	622.68	207.56	6.52	0.002
N_kg_ha	3	660.21	220.07	6.91	0.001
L_t_ha.N_kg_ha	9	701.57	77.95	2.45	0.032
Residual	30	955.53	31.85	1.49	
rep.Subject.Time stratum					
d.f. correction factor 0.4781					
Time	4	210.02	52.50	2.45	0.097
Time.L_t_ha	12	335.38	27.95	1.30	0.271
Time.N_kg_ha	12	528.85	44.07	2.05	0.075
Time.L_t_ha.N_kg_ha	36	1044.28	29.01	1.35	0.192
Residual	128	2745.07	21.45		
Total	239	8301.00			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 9	7.79	s.e. 2.00
rep 3 Subject 10	-5.38	s.e. 2.00
rep 1 Subject 1 Time ASAT_%_3	-10.13	s.e. 3.38
rep 1 Subject 7 Time ASAT_%_3	-11.67	s.e. 3.38
rep 1 Subject 9 Time ASAT_%	-13.40	s.e. 3.38
rep 1 Subject 9 Time ASAT_%_5	14.60	s.e. 3.38

Tables of means

Variate: ASAT_%,ASAT_%_3,ASAT_%_4,ASAT_%_5,ASAT_%_6

Grand mean 6.00

Time	ASAT_%	ASAT_%_3	ASAT_%_4	ASAT_%_5	ASAT_%_6
	6.42	7.67	5.27	5.38	5.29
L_t_ha	0	1	3	7	
	7.50	7.55	5.23	3.73	
N_kg_ha	0	60	120	200	
	3.87	5.03	6.98	8.13	

Time	L_t_ha	0	1	3	7
ASAT_%		10.50	6.83	5.83	2.50
ASAT_%_3		11.08	9.00	6.42	4.17
ASAT_%_4		5.33	7.50	4.42	3.83
ASAT_%_5		5.58	7.75	4.67	3.50
ASAT_%_6		5.00	6.67	4.83	4.67

Time	N_kg_ha	0	60	120	200
ASAT_%		2.83	4.25	7.33	11.25
ASAT_%_3		4.08	7.67	6.42	12.50
ASAT_%_4		3.42	4.67	6.50	6.50
ASAT_%_5		4.42	3.92	8.00	5.17
ASAT_%_6		4.58	4.67	6.67	5.25

L_t_ha	N_kg_ha	0	60	120	200
0		4.53	4.60	7.40	13.47
1		4.40	6.53	10.47	8.80
3		4.07	7.13	5.47	4.27
7		2.47	1.87	4.60	6.00

Time	L_t_ha	N_kg_ha	0	60	120	200
ASAT_%	0		3.67	5.00	13.67	19.67
	1		3.67	7.33	6.67	9.67
	3		2.00	2.33	7.33	11.67
	7		2.00	2.33	1.67	4.00
ASAT_%_3	0		5.00	5.67	8.67	25.00
	1		6.33	11.67	6.00	12.00
	3		2.67	12.00	8.00	3.00
	7		2.33	1.33	3.00	10.00
ASAT_%_4	0		3.33	4.33	4.67	9.00
	1		4.33	4.33	11.67	9.67
	3		3.33	8.00	4.33	2.00
	7		2.67	2.00	5.33	5.33
ASAT_%_5	0		5.33	4.00	5.00	8.00
	1		4.67	3.00	17.67	5.67
	3		5.67	6.67	3.67	2.67
	7		2.00	2.00	5.67	4.33
ASAT_%_6	0		5.33	4.00	5.00	5.67
	1		3.00	6.33	10.33	7.00
	3		6.67	6.67	4.00	2.00
	7		3.33	1.67	7.33	6.33

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
				L_t_ha
rep.	48	60	60	12
l.s.d.	2.127	2.104	2.104	4.433
d.f.	61.20	30	30	89.82
Except when comparing means with the same level(s) of L_t_ha				4.254
d.f.				61.20

Table	Time	L_t_ha	Time
	N_kg_ha	N_kg_ha	L_t_ha
			N_kg_ha
rep.	12	15	3
l.s.d.	4.433	4.209	8.866

d.f.	89.82	30	89.82
Except when comparing means with the same level(s) of			
N_kg_ha	4.254		
d.f.	61.20		
L_t_ha.N_kg_ha			8.509
d.f.			61.20

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: ASAT_%,ASAT_%_3,ASAT_%_4,ASAT_%_5,ASAT_%_6

Stratum		d.f.		s.e.	cv%
rep		2		1.763	29.4
rep.Subject		30		2.524	42.0
rep.Subject.Time	128	4.631	77.1		

Appendix 6.3: Chapter 6 ((NH₄)₂SO₄ and dolomitic lime) leaf statistical analysis

Analysis of variance

Variate: Al,Al_1,Al_2,Al_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	5218943.	2609471.	1.24	
rep.Subject stratum					
L_t_ha	3	5841487.	1947162.	0.93	0.439
N_kg_ha	3	9922025.	3307342.	1.58	0.215
L_t_ha.N_kg_ha	9	5309149.	589905.	0.28	0.975
Residual	30	62885165.	2096172.	1.29	
rep.Subject.Time stratum					
d.f. correction factor 0.7354					
Time	3	545604994.	181868331.	112.14	<.001
Time.L_t_ha	9	6915632.	768404.	0.47	0.842
Time.N_kg_ha	9	11934318.	1326035.	0.82	0.570
Time.L_t_ha.N_kg_ha	27	25888125.	958819.	0.59	0.905
Residual	96	155686797.	1621737.		
Total	191	835206635.			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 10	-1241.	s.e. 572.
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rep 1 Subject 14	1447.	s.e. 572.
rep 1 Subject 4 Time AI_2	2434.	s.e. 900.
rep 1 Subject 12 Time AI_2	3032.	s.e. 900.
rep 3 Subject 1 Time AI_3	2735.	s.e. 900.

Tables of means

Variate: AI,AI_1,AI_2,AI_3

Grand mean 3100.

Time	AI 631.	AI_1 2534.	AI_2 4204.	AI_3 5031.		
	L_t_ha	0 3348.	1 2855.	3 3106.	7 3092.	
	N_kg_ha	0 3249.	60 2714.	120 3279.	200 3158.	
Time	L_t_ha	0	1	3	7	
AI		666.	764.	548.	544.	
AI_1		2684.	2204.	2598.	2651.	
AI_2		4745.	4011.	4113.	3946.	
AI_3		5295.	4440.	5166.	5224.	
Time	N_kg_ha	0	60	120	200	
AI		756.	689.	618.	459.	
AI_1		2472.	2489.	2514.	2662.	
AI_2		4356.	3422.	4731.	4306.	
AI_3		5412.	4254.	5252.	5207.	
	L_t_ha	N_kg_ha	0	60	120	200
	0		3572.	2941.	3764.	3115.
	1		2998.	2568.	2738.	3114.
	3		3160.	2609.	3212.	3443.
	7		3266.	2737.	3400.	2962.
Time	L_t_ha	N_kg_ha	0	60	120	200
AI	0		570.	973.	548.	574.
	1		1092.	666.	814.	486.
	3		625.	644.	470.	452.
	7		738.	475.	638.	325.
AI_1	0		2569.	3121.	2478.	2570.
	1		2245.	2150.	2087.	2332.
	3		2367.	2462.	2655.	2908.
	7		2710.	2223.	2834.	2838.
AI_2	0		5054.	2959.	5981.	4986.
	1		4370.	3981.	3747.	3946.
	3		3995.	2625.	4890.	4941.
	7		4005.	4124.	4306.	3351.
AI_3	0		6094.	4710.	6048.	4329.
	1		4284.	3475.	4306.	5694.
	3		5655.	4706.	4834.	5471.
	7		5613.	4127.	5822.	5336.

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	48	48	12
l.s.d.	546.1	603.6	603.6	1126.1
d.f.	70.60	30	30	100.59
Except when comparing means with the same level(s) of L_t_ha				1092.2
d.f.				70.60

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	1126.1	1207.1	2252.2
d.f.	100.59	30	100.59
Except when comparing means with the same level(s) of N_kg_ha			
d.f.	1092.2		
L_t_ha.N_kg_ha			2184.4
d.f.	70.60		70.60

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: AI,AI_1,AI_2,AI_3

Stratum	d.f.	s.e.	cv%
rep	2	201.9	6.5
rep.Subject	30	723.9	23.4
rep.Subject.Time	96	1273.5	41.1

Analysis of variance

Variate: B,B_1,B_2,B_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	1075.06	537.53	19.95	
rep.Subject stratum					
L_t_ha	3	308.48	102.83	3.82	0.020
N_kg_ha	3	39.00	13.00	0.48	0.697
L_t_ha.N_kg_ha	9	239.42	26.60	0.99	0.471
Residual	30	808.49	26.95	0.95	
rep.Subject.Time stratum					
d.f. correction factor 0.6875					
Time	3	5057.81	1685.94	59.46	<.001
Time.L_t_ha	9	282.03	31.34	1.11	0.369
Time.N_kg_ha	9	220.32	24.48	0.86	0.529
Time.L_t_ha.N_kg_ha	27	565.40	20.94	0.74	0.763
Residual	96	2721.95	28.35		
Total	191	11317.95			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 16	4.95	s.e. 2.05
rep 3 Subject 13	4.98	s.e. 2.05
rep 1 Subject 5 Time B_2	12.84	s.e. 3.77
rep 1 Subject 7 Time B_3	13.06	s.e. 3.77
rep 2 Subject 2 Time B_2	-10.74	s.e. 3.77

Tables of means

Variate: B,B_1,B_2,B_3

Grand mean 17.40

Time	B	B_1	B_2	B_3
	14.51	10.62	23.71	20.75

L_t_ha	0	1	3	7
	16.49	16.31	19.50	17.29

N_kg_ha	0	60	120	200
	17.90	17.35	16.69	17.64

Time	L_t_ha	0	1	3	7
B		13.27	14.44	14.94	15.39
B_1		9.49	10.48	11.29	11.22
B_2		24.57	21.48	26.31	22.50
B_3		18.65	18.84	25.45	20.05

Time	N_kg_ha	0	60	120	200
B		14.70	15.17	13.87	14.29
B_1		11.43	10.95	9.15	10.96
B_2		23.89	21.38	25.53	24.06
B_3		21.60	21.92	18.22	21.25

L_t_ha	N_kg_ha	0	60	120	200
0		18.97	16.39	15.34	15.28
1		18.32	15.28	15.66	15.98
3		17.64	20.32	18.83	21.20
7		16.69	17.43	16.94	18.11

Time	L_t_ha	N_kg_ha	0	60	120	200
B	0		15.45	14.28	11.94	11.39
	1		15.36	12.70	15.77	13.95
	3		13.53	16.72	13.29	16.21
	7		14.45	17.00	14.48	15.62
B_1	0		10.91	9.18	7.68	10.20
	1		12.42	10.07	8.40	11.02
	3		10.32	12.07	11.33	11.46

	7	12.06	12.48	9.19	11.17
B_2	0	28.66	23.16	22.96	23.49
	1	22.61	20.36	22.52	20.43
	3	23.86	19.89	32.92	28.58
	7	20.41	22.11	23.73	23.74
B_3	0	20.84	18.92	18.80	16.03
	1	22.88	18.01	15.95	18.51
	3	22.84	32.59	17.79	28.56
	7	19.82	18.14	20.34	21.90

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	48	48	12
l.s.d.	2.311	2.164	2.164	4.571
d.f.	66.00	30	30	93.74
Except when comparing means with the same level(s) of L_t_ha				4.623
d.f.				66.00

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	4.571	4.328	9.143
d.f.	93.74	30	93.74
Except when comparing means with the same level(s) of N_kg_ha			
d.f.	4.623		
L_t_ha.N_kg_ha	66.00		9.245
d.f.			66.00

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: B,B_1,B_2,B_3

Stratum	d.f.	s.e.	cv%
rep	2	2.898	16.7
rep.Subject	30	2.596	14.9
rep.Subject.Time	96	5.325	30.6

Analysis of variance

Variate: Ca,Ca_1,Ca_2,Ca_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.45635	0.22818	6.62	
rep.Subject stratum					
L_t_ha	3	0.56864	0.18955	5.50	0.004
N_kg_ha	3	0.16383	0.05461	1.58	0.214
L_t_ha.N_kg_ha	9	0.47780	0.05309	1.54	0.179
Residual	30	1.03452	0.03448	1.77	
rep.Subject.Time stratum					
d.f. correction factor 0.9548					
Time	3	2.93298	0.97766	50.12	<.001
Time.L_t_ha	9	0.26528	0.02948	1.51	0.159
Time.N_kg_ha	9	0.27565	0.03063	1.57	0.139
Time.L_t_ha.N_kg_ha	27	0.42513	0.01575	0.81	0.727
Residual	96	1.87252	0.01951		
Total	191	8.47270			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 4	-0.196	s.e. 0.073
rep 2 Subject 1	-0.194	s.e. 0.073
rep 1 Subject 9 Time Ca_2	-0.262	s.e. 0.099
rep 3 Subject 10 Time Ca_2	0.264	s.e. 0.099
rep 3 Subject 10 Time Ca_3	-0.257	s.e. 0.099

Tables of means

Variate: Ca,Ca_1,Ca_2,Ca_3

Grand mean 0.934

Time	Ca	Ca_1	Ca_2	Ca_3
	0.921	0.749	0.974	1.093
L_t_ha	0	1	3	7
	0.880	0.904	0.930	1.023
N_kg_ha	0	60	120	200
	0.979	0.934	0.924	0.899

Time	L_t_ha	0	1	3	7
Ca		0.903	0.912	0.904	0.964
Ca_1		0.728	0.726	0.747	0.795
Ca_2		0.879	0.980	0.942	1.094
Ca_3		1.008	0.996	1.126	1.240

Time	N_kg_ha	0	60	120	200
Ca		0.986	0.940	0.874	0.882
Ca_1		0.811	0.799	0.685	0.701
Ca_2		0.999	0.906	1.059	0.931
Ca_3		1.120	1.093	1.077	1.080

L_t_ha	N_kg_ha	0	60	120	200
0		0.948	0.979	0.808	0.783
1		0.961	0.828	0.964	0.861
3		0.966	0.961	0.871	0.921
7		1.042	0.969	1.052	1.030

Time	L_t_ha	N_kg_ha	0	60	120	200
Ca	0		0.964	1.029	0.846	0.775
	1		1.024	0.814	0.868	0.941
	3		0.929	0.964	0.841	0.882
	7		1.028	0.953	0.942	0.932
Ca_1	0		0.823	0.813	0.617	0.660
	1		0.765	0.734	0.740	0.666
	3		0.856	0.751	0.685	0.694
	7		0.801	0.898	0.698	0.783
Ca_2	0		1.021	0.897	0.834	0.762
	1		1.049	0.818	1.183	0.872
	3		0.863	0.955	0.990	0.960
	7		1.063	0.953	1.229	1.129
Ca_3	0		0.986	1.177	0.937	0.934
	1		1.007	0.946	1.065	0.965
	3		1.214	1.175	0.969	1.147
	7		1.275	1.074	1.338	1.275

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
rep.	48	48	48	L_t_ha
l.s.d.	0.0571	0.0774	0.0774	0.1243
d.f.	91.66	30	30	112.33
Except when comparing means with the same level(s) of L_t_ha				0.1142
d.f.				91.66

Table	Time	L_t_ha	Time
	N_kg_ha	N_kg_ha	L_t_ha
rep.	12	12	N_kg_ha
l.s.d.	0.1243	0.1548	0.2487
d.f.	112.33	30	112.33
Except when comparing means with the same level(s) of N_kg_ha			0.2283
d.f.	91.66		91.66
L_t_ha.N_kg_ha			
d.f.			

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Ca,Ca_1,Ca_2,Ca_3

Stratum	d.f.	s.e.	cv%
rep	2	0.0597	6.4
rep.Subject	30	0.0928	9.9
rep.Subject.Time	96	0.1397	15.0

Analysis of variance

Variate: Cu,Cu_1,Cu_2,Cu_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	381.545	190.772	34.56	
rep.Subject stratum					
L_t_ha	3	106.721	35.574	6.44	0.002
N_kg_ha	3	45.604	15.201	2.75	0.060
L_t_ha.N_kg_ha	9	126.637	14.071	2.55	0.026
Residual	30	165.622	5.521	0.83	
rep.Subject.Time stratum					
d.f. correction factor 0.7696					
Time	3	641.687	213.896	32.15	<.001
Time.L_t_ha	9	44.088	4.899	0.74	0.641
Time.N_kg_ha	9	44.973	4.997	0.75	0.628
Time.L_t_ha.N_kg_ha	27	152.401	5.644	0.85	0.653
Residual	96	638.781	6.654		
Total	191	2348.057			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 11	-2.06	s.e. 0.93
rep 2 Subject 14	-2.09	s.e. 0.93
rep 1 Subject 7 Time Cu_1	5.31	s.e. 1.82
rep 1 Subject 13 Time Cu_3	5.22	s.e. 1.82
rep 2 Subject 12 Time Cu_3	5.10	s.e. 1.82
rep 2 Subject 13 Time Cu_1	-5.51	s.e. 1.82

Tables of means

Variate: Cu,Cu_1,Cu_2,Cu_3

Grand mean 17.47

Time	Cu	Cu_1	Cu_2	Cu_3
	15.39	17.85	16.38	20.24

L_t_ha	0	1	3	7
	18.18	17.99	17.43	16.26

N_kg_ha	0	60	120	200
	16.74	17.40	17.64	18.08

Time	L_t_ha	0	1	3	7
Cu		15.73	15.97	15.21	14.65
Cu_1		18.72	18.47	17.22	16.99
Cu_2		17.79	17.02	16.76	13.95
Cu_3		20.48	20.48	20.54	19.47

Time	N_kg_ha	0	60	120	200
Cu		14.36	15.74	15.41	16.05
Cu_1		16.45	17.51	18.95	18.49
Cu_2		15.62	16.22	16.08	17.58
Cu_3		20.51	20.13	20.13	20.21

L_t_ha	N_kg_ha	0	60	120	200
0		15.82	17.62	19.56	19.72
1		16.99	18.92	17.40	18.63
3		17.76	17.43	17.63	16.91
7		16.37	15.62	15.99	17.07

Time	L_t_ha	N_kg_ha	0	60	120	200
Cu	0		13.06	15.60	17.02	17.24
	1		15.58	17.78	14.74	15.79
	3		15.20	15.94	14.66	15.02
	7		13.59	13.66	15.21	16.13
Cu_1	0		17.10	17.46	20.02	20.30
	1		16.63	18.88	19.21	19.16
	3		14.89	17.82	18.87	17.28
	7		17.18	15.86	17.71	17.22
Cu_2	0		13.94	15.90	20.50	20.80
	1		15.57	19.30	14.40	18.79
	3		19.09	14.89	16.73	16.34
	7		13.89	14.80	12.70	14.39
Cu_3	0		19.17	21.52	20.70	20.53
	1		20.20	19.73	21.24	20.77
	3		21.85	21.08	20.24	18.99
	7		20.81	18.18	18.35	20.55

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
rep.	48	48	48	L_t_ha
l.s.d.	1.097	0.980	0.980	12
d.f.	73.88	30	30	2.138
				101.32

Except when comparing means with the same level(s) of
L_t_ha
d.f.

2.194
73.88

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	2.138	1.959	4.276
d.f.	101.32	30	101.32
Except when comparing means with the same level(s) of			
N_kg_ha	2.194		
d.f.	73.88		
L_t_ha.N_kg_ha			4.388
d.f.			73.88

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Cu,Cu_1,Cu_2,Cu_3

Stratum	d.f.	s.e.	cv%
rep	2	1.727	9.9
rep.Subject	30	1.175	6.7
rep.Subject.Time	96	2.580	14.8

Analysis of variance

Variate: Fe,Fe_1,Fe_2,Fe_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	554129.	277065.	0.46	
rep.Subject stratum					
L_t_ha	3	1667916.	555972.	0.92	0.442
N_kg_ha	3	2695313.	898438.	1.49	0.237
L_t_ha.N_kg_ha	9	750913.	83435.	0.14	0.998
Residual	30	18092462.	603082.	1.29	
rep.Subject.Time stratum					
d.f. correction factor 0.7282					
Time	3	112953190.	37651063.	80.47	<.001
Time.L_t_ha	9	1404749.	156083.	0.33	0.928
Time.N_kg_ha	9	3449907.	383323.	0.82	0.568
Time.L_t_ha.N_kg_ha	27	5149901.	190737.	0.41	0.986
Residual	96	44917787.	467894.		
Total	191	191636267.			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 14	912.	s.e. 307.
rep 1 Subject 12 Time Fe_2	1633.	s.e. 484.
rep 3 Subject 1 Time Fe_3	1454.	s.e. 484.

Tables of means

Variate: Fe,Fe_1,Fe_2,Fe_3

Grand mean 1565.

Time	Fe 482.	Fe_1 1223.	Fe_2 2124.	Fe_3 2431.		
	L_t_ha	0 1724.	1 1487.	3 1518.	7 1531.	
	N_kg_ha	0 1596.	60 1365.	120 1670.	200 1629.	
Time	L_t_ha	0	1	3	7	
Fe		507.	590.	429.	402.	
Fe_1		1321.	1095.	1239.	1235.	
Fe_2		2394.	2051.	2017.	2034.	
Fe_3		2674.	2210.	2388.	2453.	
Time	N_kg_ha	0	60	120	200	
Fe		525.	517.	485.	400.	
Fe_1		1186.	1167.	1270.	1267.	
Fe_2		2094.	1652.	2449.	2300.	
Fe_3		2580.	2122.	2473.	2549.	
	L_t_ha	N_kg_ha	0	60	120	200
	0		1787.	1452.	1935.	1721.
	1		1505.	1360.	1487.	1595.
	3		1510.	1247.	1669.	1647.
	7		1583.	1399.	1587.	1555.
Time	L_t_ha	N_kg_ha	0	60	120	200
Fe	0		407.	637.	443.	540.
	1		751.	604.	585.	421.
	3		464.	454.	453.	344.
	7		478.	374.	460.	295.
Fe_1	0		1270.	1453.	1304.	1257.
	1		1103.	1011.	1102.	1165.
	3		1125.	1170.	1354.	1308.
	7		1246.	1036.	1321.	1338.
Fe_2	0		2532.	1393.	2975.	2674.
	1		2030.	2044.	2066.	2064.
	3		1791.	1238.	2669.	2368.
	7		2022.	1934.	2086.	2096.
Fe_3	0		2940.	2327.	3020.	2411.
	1		2135.	1782.	2192.	2729.
	3		2660.	2127.	2201.	2566.

7 2586. 2253. 2481. 2491.

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	48	48	12
l.s.d.	293.9	323.7	323.7	605.7
d.f.	69.90	30	30	99.90
Except when comparing means with the same level(s) of L_t_ha				587.7
d.f.				69.90

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	605.7	647.5	1211.3
d.f.	99.90	30	99.90
Except when comparing means with the same level(s) of N_kg_ha			587.7
d.f.	69.90		
L_t_ha.N_kg_ha			1175.4
d.f.			69.90

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Fe,Fe_1,Fe_2,Fe_3

Stratum	d.f.	s.e.	cv%
rep	2	65.8	4.2
rep.Subject	30	388.3	24.8
rep.Subject.Time	96	684.0	43.7

Analysis of variance

Variate: K,K_1,K_2,K_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.9462	0.4731	1.62	
rep.Subject stratum					
L_t_ha	3	0.3103	0.1034	0.35	0.786
N_kg_ha	3	1.0235	0.3412	1.17	0.338
L_t_ha.N_kg_ha	9	4.7519	0.5280	1.81	0.108
Residual	30	8.7629	0.2921	0.83	
rep.Subject.Time stratum					
d.f. correction factor 0.7282					
Time	3	22.4847	7.4949	21.19	<.001
Time.L_t_ha	9	2.3645	0.2627	0.74	0.628
Time.N_kg_ha	9	1.4418	0.1602	0.45	0.855
Time.L_t_ha.N_kg_ha	27	5.4609	0.2023	0.57	0.918
Residual	96	33.9599	0.3537		

Total 191 81.5068

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 3 Subject 9	-0.533	s.e. 0.214
rep 1 Subject 13 Time K_2	1.265	s.e. 0.421
rep 1 Subject 14 Time K_2	1.173	s.e. 0.421
rep 1 Subject 15 Time K_2	1.168	s.e. 0.421
rep 2 Subject 6 Time K_2	-1.217	s.e. 0.421
rep 3 Subject 7 Time K_2	-1.346	s.e. 0.421
rep 3 Subject 8 Time K	1.235	s.e. 0.421

Tables of means

Variate: K,K_1,K_2,K_3

Grand mean 4.684

Time	K	K_1	K_2	K_3		
	4.780	4.607	5.150	4.198		
L_t_ha	0	1	3	7		
	4.619	4.729	4.693	4.694		
N_kg_ha	0	60	120	200		
	4.804	4.663	4.607	4.660		
Time	L_t_ha	0	1	3	7	
K		4.721	4.706	4.669	5.023	
K_1		4.531	4.811	4.604	4.484	
K_2		5.221	5.186	5.158	5.034	
K_3		4.002	4.214	4.339	4.237	
Time	N_kg_ha	0	60	120	200	
K		4.864	4.750	4.716	4.789	
K_1		4.732	4.748	4.437	4.512	
K_2		5.271	4.936	5.118	5.274	
K_3		4.349	4.220	4.159	4.063	
L_t_ha	N_kg_ha	0	60	120	200	
0		5.006	4.598	4.348	4.524	
1		4.798	4.921	4.393	4.804	
3		4.734	4.512	4.846	4.678	
7		4.679	4.623	4.842	4.634	
Time	L_t_ha	N_kg_ha	0	60	120	200
K	0		5.197	4.496	4.469	4.724
	1		4.502	4.748	4.642	4.930

	3	5.109	4.478	4.554	4.535
	7	4.649	5.277	5.197	4.969
K_1	0	4.831	4.725	4.383	4.184
	1	4.918	5.056	4.348	4.923
	3	4.519	4.853	4.577	4.468
	7	4.662	4.358	4.440	4.475
K_2	0	5.522	5.056	4.773	5.534
	1	5.564	5.350	4.699	5.131
	3	5.060	4.509	5.636	5.428
	7	4.938	4.829	5.365	5.004
K_3	0	4.472	4.114	3.768	3.653
	1	4.210	4.531	3.884	4.231
	3	4.247	4.209	4.618	4.281
	7	4.467	4.027	4.365	4.087

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
				L_t_ha
rep.	48	48	48	12
l.s.d.	0.2555	0.2253	0.2253	0.4976
d.f.	69.91	30	30	96.63
Except when comparing means with the same level(s) of				
L_t_ha				0.5110
d.f.				69.91

Table	Time	L_t_ha	Time
	N_kg_ha	N_kg_ha	L_t_ha
			N_kg_ha
rep.	12	12	3
l.s.d.	0.4976	0.4506	0.9951
d.f.	96.63	30	96.63
Except when comparing means with the same level(s) of			
N_kg_ha	0.5110		
d.f.	69.91		
L_t_ha.N_kg_ha			1.0220
d.f.			69.91

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: K,K_1,K_2,K_3

Stratum	d.f.	s.e.	cv%
rep	2	0.0860	1.8
rep.Subject	30	0.2702	5.8
rep.Subject.Time	96	0.5948	12.7

Analysis of variance

Variate: Mg,Mg_1,Mg_2,Mg_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.069262	0.034631	11.83	

rep.Subject stratum					
L_t_ha	3	0.008530	0.002843	0.97	0.419
N_kg_ha	3	0.003851	0.001284	0.44	0.727
L_t_ha.N_kg_ha	9	0.022885	0.002543	0.87	0.562
Residual	30	0.087785	0.002926	2.05	
rep.Subject.Time stratum					
d.f. correction factor 0.8418					
Time	3	0.249976	0.083325	58.40	<.001
Time.L_t_ha	9	0.011520	0.001280	0.90	0.519
Time.N_kg_ha	9	0.017404	0.001934	1.36	0.232
Time.L_t_ha.N_kg_ha	27	0.033051	0.001224	0.86	0.650
Residual	96	0.136984	0.001427		
Total	191	0.641248			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 6	0.0519	s.e.	0.0214
rep 1 Subject 12 Time Mg_2	-0.0809	s.e.	0.0267
rep 1 Subject 13 Time Mg_3	0.0722	s.e.	0.0267
rep 2 Subject 4 Time Mg	-0.0689	s.e.	0.0267
rep 2 Subject 16 Time Mg_2	0.0724	s.e.	0.0267

Tables of means

Variate: Mg,Mg_1,Mg_2,Mg_3

Grand mean 0.3728

Time	Mg	Mg_1	Mg_2	Mg_3	
	0.3558	0.3306	0.4288	0.3760	
L_t_ha	0	1	3	7	
	0.3672	0.3792	0.3652	0.3797	
N_kg_ha	0	60	120	200	
	0.3782	0.3738	0.3735	0.3658	
Time	L_t_ha	0	1	3	7
Mg		0.3531	0.3712	0.3488	0.3502
Mg_1		0.3267	0.3255	0.3255	0.3449
Mg_2		0.4189	0.4471	0.4087	0.4403
Mg_3		0.3701	0.3729	0.3778	0.3835
Time	N_kg_ha	0	60	120	200
Mg		0.3672	0.3550	0.3478	0.3533
Mg_1		0.3193	0.3355	0.3323	0.3354
Mg_2		0.4495	0.4224	0.4411	0.4021

Mg_3		0.3768	0.3821	0.3731	0.3723	
	L_t_ha	N_kg_ha	0	60	120	200
	0		0.3686	0.3800	0.3692	0.3510
	1		0.3795	0.3765	0.4000	0.3607
	3		0.3725	0.3766	0.3491	0.3625
	7		0.3922	0.3619	0.3760	0.3888
Time	L_t_ha	N_kg_ha	0	60	120	200
Mg	0		0.3471	0.3654	0.3567	0.3433
	1		0.3859	0.3852	0.3576	0.3561
	3		0.3395	0.3537	0.3334	0.3684
	7		0.3963	0.3157	0.3434	0.3454
Mg_1	0		0.3165	0.3395	0.3148	0.3360
	1		0.3026	0.3335	0.3525	0.3133
	3		0.3279	0.3156	0.3224	0.3361
	7		0.3303	0.3535	0.3394	0.3562
Mg_2	0		0.4477	0.4163	0.4461	0.3657
	1		0.4622	0.4207	0.4899	0.4158
	3		0.4201	0.4388	0.4021	0.3738
	7		0.4678	0.4140	0.4262	0.4530
Mg_3	0		0.3633	0.3988	0.3591	0.3592
	1		0.3673	0.3667	0.3998	0.3576
	3		0.4023	0.3984	0.3385	0.3718
	7		0.3742	0.3645	0.3949	0.4004

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	48	48	12
l.s.d.	0.01580	0.02255	0.02255	0.03541
d.f.	80.81	30	30	101.41
Except when comparing means with the same level(s) of L_t_ha				0.03161
d.f.				80.81

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	0.03541	0.04510	0.07083
d.f.	101.41	30	101.41
Except when comparing means with the same level(s) of N_kg_ha			0.06321
d.f.	80.81		80.81
L_t_ha.N_kg_ha			0.06321
d.f.			80.81

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Mg,Mg_1,Mg_2,Mg_3

Stratum	d.f.	s.e.	cv%
rep	2	0.02326	6.2

rep.Subject	30	0.02705	7.3
rep.Subject.Time	96	0.03777	10.1

Analysis of variance

Variate: Mn,Mn_1,Mn_2,Mn_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	9279.	4640.	0.62	
rep.Subject stratum					
L_t_ha	3	132632.	44211.	5.87	0.003
N_kg_ha	3	45981.	15327.	2.03	0.130
L_t_ha.N_kg_ha	9	57074.	6342.	0.84	0.585
Residual	30	226069.	7536.	2.56	
rep.Subject.Time stratum					
d.f. correction factor 0.4552					
Time	3	267206.	89069.	30.26	<.001
Time.L_t_ha	9	24570.	2730.	0.93	0.459
Time.N_kg_ha	9	42009.	4668.	1.59	0.194
Time.L_t_ha.N_kg_ha	27	77057.	2854.	0.97	0.492
Residual	96	282598.	2944.		
Total	191	1164475.			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 14	84.5	s.e. 34.3
rep 1 Subject 10 Time Mn_2	-100.9	s.e. 38.4
rep 1 Subject 14 Time Mn_1	-103.0	s.e. 38.4
rep 1 Subject 14 Time Mn_2	178.3	s.e. 38.4
rep 2 Subject 8 Time Mn_2	154.0	s.e. 38.4
rep 2 Subject 15 Time Mn_2	108.5	s.e. 38.4
rep 3 Subject 12 Time Mn_2	106.1	s.e. 38.4

Tables of means

Variate: Mn,Mn_1,Mn_2,Mn_3

Grand mean 133.4

Time	Mn	Mn_1	Mn_2	Mn_3
	88.4	104.7	170.6	169.9
L_t_ha		0	1	3
				7

		167.4	144.9	125.4	95.9
	N_kg_ha	0	60	120	200
		113.2	124.0	144.7	151.7
Time	L_t_ha	0	1	3	7
Mn		114.5	100.2	76.9	61.9
Mn_1		122.1	118.5	106.4	71.9
Mn_2		229.3	190.7	148.7	113.6
Mn_3		203.8	170.4	169.4	136.2
Time	N_kg_ha	0	60	120	200
Mn		81.9	87.5	96.9	87.1
Mn_1		95.9	113.7	103.3	106.0
Mn_2		125.0	154.3	193.3	209.8
Mn_3		150.1	140.4	185.2	204.1

	L_t_ha	N_kg_ha	0	60	120	200
	0		128.7	129.4	192.4	219.2
	1		116.5	156.4	147.8	159.0
	3		125.8	101.9	141.1	132.6
	7		81.9	108.2	97.3	96.2

Time	L_t_ha	N_kg_ha	0	60	120	200
Mn	0		82.2	113.8	120.9	141.1
	1		98.2	111.0	105.2	86.3
	3		87.7	69.7	88.1	62.0
	7		59.5	55.7	73.6	58.9
Mn_1	0		91.0	138.4	120.7	138.3
	1		110.1	128.5	117.2	118.3
	3		110.2	99.1	113.4	103.1
	7		72.4	89.0	61.9	64.4
Mn_2	0		174.4	100.0	304.5	338.4
	1		118.4	235.0	188.5	220.8
	3		121.2	107.3	185.7	180.7
	7		86.1	174.7	94.4	99.1
Mn_3	0		167.3	165.4	223.7	258.9
	1		139.4	151.3	180.3	210.5
	3		184.0	131.5	177.4	184.7
	7		109.7	113.4	159.4	162.3

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
				L_t_ha
rep.	48	48	48	12
l.s.d.	25.25	36.19	36.19	59.02
d.f.	43.70	30	30	72.84

Except when comparing means with the same level(s) of L_t_ha

d.f. 50.50

Table	Time	L_t_ha	Time
	N_kg_ha	N_kg_ha	L_t_ha
			N_kg_ha
rep.	12	12	3
l.s.d.	59.02	72.38	118.03
d.f.	72.84	30	72.84

Except when comparing means with the same level(s) of

N_kg_ha	50.50	
d.f.	43.70	
L_t_ha.N_kg_ha		101.01
d.f.		43.70

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Mn,Mn_1,Mn_2,Mn_3

Stratum	d.f.	s.e.	cv%
rep	2	8.51	6.4
rep.Subject	30	43.40	32.5
rep.Subject.Time	96	54.26	40.7

Analysis of variance

Variate: N,N_1,N_2,N_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.22203	0.11102	1.17	
rep.Subject stratum					
L_t_ha	3	0.15078	0.05026	0.53	0.665
N_kg_ha	3	2.61261	0.87087	9.18	<.001
L_t_ha.N_kg_ha	9	1.31873	0.14653	1.54	0.178
Residual	30	2.84546	0.09485	1.40	
rep.Subject.Time stratum					
d.f. correction factor 0.9276					
Time	3	10.01795	3.33932	49.37	<.001
Time.L_t_ha	9	0.80598	0.08955	1.32	0.240
Time.N_kg_ha	9	0.71600	0.07956	1.18	0.322
Time.L_t_ha.N_kg_ha	27	1.39717	0.05175	0.77	0.774
Residual	96	6.49328	0.06764		
Total	191	26.57998			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 11	-0.264	s.e. 0.122
rep 2 Subject 1	0.321	s.e. 0.122
rep 2 Subject 14	-0.398	s.e. 0.122
rep 2 Subject 10 Time N_3	-0.500	s.e. 0.184
rep 3 Subject 1 Time N_1	-0.488	s.e. 0.184

rep 3 Subject 8 Time N	0.597	s.e. 0.184
rep 3 Subject 10 Time N	0.493	s.e. 0.184

Tables of means

Variate: N,N_1,N_2,N_3

Grand mean 3.146

Time	N	N_1	N_2	N_3		
	3.478	3.217	3.023	2.866		
L_t_ha	0	1	3	7		
	3.116	3.139	3.192	3.137		
N_kg_ha	0	60	120	200		
	2.970	3.113	3.233	3.268		
Time	L_t_ha	0	1	3	7	
N		3.345	3.589	3.460	3.519	
N_1		3.212	3.192	3.248	3.215	
N_2		3.118	2.934	3.103	2.936	
N_3		2.787	2.843	2.957	2.879	
Time	N_kg_ha	0	60	120	200	
N		3.167	3.438	3.631	3.677	
N_1		3.012	3.158	3.357	3.339	
N_2		2.958	2.988	3.050	3.095	
N_3		2.743	2.868	2.895	2.959	
L_t_ha	N_kg_ha	0	60	120	200	
0		2.887	3.052	3.261	3.263	
1		2.967	3.267	3.089	3.235	
3		3.120	3.160	3.228	3.259	
7		2.906	2.973	3.355	3.314	
Time	L_t_ha	N_kg_ha	0	60	120	200
N	0		2.913	3.098	3.680	3.691
	1		3.238	3.796	3.557	3.766
	3		3.386	3.462	3.543	3.448
	7		3.130	3.396	3.744	3.806
N_1	0		2.840	3.221	3.421	3.366
	1		3.109	3.268	3.129	3.261
	3		3.123	3.143	3.302	3.423
	7		2.976	3.001	3.576	3.308
N_2	0		3.097	2.914	3.259	3.202
	1		2.873	3.157	2.819	2.889
	3		3.114	3.032	3.102	3.163
	7		2.748	2.848	3.019	3.127
N_3	0		2.698	2.975	2.683	2.793
	1		2.649	2.847	2.850	3.025
	3		2.857	3.002	2.967	3.003
	7		2.770	2.647	3.081	3.016

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	48	48	12
l.s.d.	0.1069	0.1284	0.1284	0.2235
d.f.	89.05	30	30	116.32
Except when comparing means with the same level(s) of L_t_ha				0.2137
d.f.				89.05

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	0.2235	0.2568	0.4470
d.f.	116.32	30	116.32
Except when comparing means with the same level(s) of N_kg_ha			0.2137
d.f.	89.05		
L_t_ha.N_kg_ha			0.4275
d.f.			89.05

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: N,N_1,N_2,N_3

Stratum	d.f.	s.e.	cv%
rep	2	0.0416	1.3
rep.Subject	30	0.1540	4.9
rep.Subject.Time	96	0.2601	8.3

Analysis of variance

Variate: Na,Na_1,Na_2,Na_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	626907.	313454.	0.11	
rep.Subject stratum					
L_t_ha	3	16978210.	5659403.	1.93	0.146
N_kg_ha	3	2034463.	678154.	0.23	0.874
L_t_ha.N_kg_ha	9	48327103.	5369678.	1.83	0.104
Residual	30	88091697.	2936390.	1.04	
rep.Subject.Time stratum					
d.f. correction factor 0.5506					
Time	3	349049656.	116349885.	41.11	<.001
Time.L_t_ha	9	21491955.	2387995.	0.84	0.524
Time.N_kg_ha	9	32875996.	3652888.	1.29	0.282
Time.L_t_ha.N_kg_ha	27	67374589.	2495355.	0.88	0.587
Residual	96	271728393.	2830504.		
Total	191	898578969.			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 10	-1466.	s.e. 677.
rep 1 Subject 15 Time Na_2	-3058.	s.e. 1190.
rep 2 Subject 4 Time Na_2	4597.	s.e. 1190.
rep 2 Subject 6 Time Na_2	3706.	s.e. 1190.
rep 2 Subject 16 Time Na_2	3603.	s.e. 1190.

Tables of means

Variate: Na,Na_1,Na_2,Na_3

Grand mean 10281.

Time	Na	Na_1	Na_2	Na_3
	9129.	8794.	11954.	11248.

L_t_ha	0	1	3	7
	10565.	10484.	10277.	9800.

N_kg_ha	0	60	120	200
	10184.	10256.	10454.	10232.

Time	L_t_ha	0	1	3	7
Na		9805.	9388.	9162.	8162.
Na_1		9173.	8639.	8666.	8700.
Na_2		11531.	12655.	11807.	11823.
Na_3		11753.	11253.	11474.	10514.

Time	N_kg_ha	0	60	120	200
Na		8948.	9086.	8944.	9538.
Na_1		8552.	8363.	9178.	9085.
Na_2		12585.	12301.	12034.	10895.
Na_3		10652.	11274.	11660.	11408.

L_t_ha	N_kg_ha	0	60	120	200
0		9845.	10623.	10999.	10795.
1		10638.	10008.	11248.	10040.
3		10161.	11299.	9916.	9732.
7		10093.	9094.	9654.	10359.

Time	L_t_ha	N_kg_ha	0	60	120	200
Na	0		8340.	10205.	10211.	10463.
	1		9430.	9796.	8870.	9456.
	3		8810.	9373.	8966.	9498.
	7		9212.	6970.	7730.	8735.
Na_1	0		8526.	8707.	9233.	10225.
	1		8230.	8100.	9990.	8237.
	3		8747.	8061.	8761.	9094.

	7	8705.	8583.	8726.	8786.
Na_2	0	11471.	11332.	13056.	10268.
	1	14206.	11628.	13793.	10992.
	3	12163.	14963.	10441.	9661.
	7	12500.	11283.	10848.	12661.
Na_3	0	11044.	12248.	11495.	12224.
	1	10686.	10511.	12339.	11477.
	3	10923.	12799.	11495.	10677.
	7	9955.	9538.	11310.	11253.

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	48	48	12
l.s.d.	759.1	714.4	714.4	1515.4
d.f.	52.86	30	30	79.08
Except when comparing means with the same level(s) of L_t_ha				1518.1
d.f.				52.86

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	1515.4	1428.7	3030.8
d.f.	79.08	30	79.08
Except when comparing means with the same level(s) of N_kg_ha			1518.1
d.f.	52.86		
L_t_ha.N_kg_ha			3036.3
d.f.			52.86

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Na,Na_1,Na_2,Na_3

Stratum	d.f.	s.e.	cv%
rep	2	70.0	0.7
rep.Subject	30	856.8	8.3
rep.Subject.Time	96	1682.4	16.4

Analysis of variance

Variate: P,P_1,P_2,P_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.031673	0.015837	6.14	
rep.Subject stratum					
L_t_ha	3	0.024118	0.008039	3.12	0.041
N_kg_ha	3	0.003884	0.001295	0.50	0.684
L_t_ha.N_kg_ha	9	0.005159	0.000573	0.22	0.989

Residual	30	0.077330	0.002578	1.33	
rep.Subject.Time stratum					
d.f. correction factor 0.8521					
Time	3	0.263670	0.087890	45.46	<.001
Time.L_t_ha	9	0.012142	0.001349	0.70	0.687
Time.N_kg_ha	9	0.002315	0.000257	0.13	0.997
Time.L_t_ha.N_kg_ha	27	0.030736	0.001138	0.59	0.925
Residual	96	0.185620	0.001934		
Total	191	0.636648			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 6 Time P	-0.0814	s.e. 0.0311
rep 1 Subject 15 Time P_2	0.0815	s.e. 0.0311
rep 3 Subject 3 Time P_2	0.0984	s.e. 0.0311
rep 3 Subject 8 Time P	0.1073	s.e. 0.0311

Tables of means

Variate: P,P_1,P_2,P_3

Grand mean 0.3047

Time	P	P_1	P_2	P_3	
	0.3569	0.3137	0.2942	0.2539	
L_t_ha	0	1	3	7	
	0.2910	0.2964	0.3135	0.3177	
N_kg_ha	0	60	120	200	
	0.3094	0.3089	0.3002	0.3001	
Time	L_t_ha	0	1	3	7
P		0.3401	0.3512	0.3647	0.3713
P_1		0.3062	0.3140	0.3095	0.3250
P_2		0.2710	0.2760	0.3237	0.3060
P_3		0.2466	0.2445	0.2559	0.2685
Time	N_kg_ha	0	60	120	200
P		0.3557	0.3651	0.3534	0.3532
P_1		0.3214	0.3119	0.3155	0.3060
P_2		0.2991	0.3004	0.2850	0.2923
P_3		0.2614	0.2583	0.2469	0.2490
L_t_ha	N_kg_ha	0	60	120	200
0		0.2973	0.3019	0.2880	0.2768
1		0.3001	0.3029	0.2879	0.2948
3		0.3200	0.3202	0.3073	0.3064

	7	0.3202	0.3107	0.3175	0.3225	
Time	L_t_ha	N_kg_ha	0	60	120	200
P	0		0.3566	0.3249	0.3483	0.3307
	1		0.3493	0.3689	0.3399	0.3467
	3		0.3668	0.3678	0.3666	0.3578
	7		0.3501	0.3987	0.3588	0.3777
P_1	0		0.3232	0.2966	0.3076	0.2975
	1		0.3275	0.3221	0.3062	0.3004
	3		0.2919	0.3341	0.3074	0.3047
	7		0.3430	0.2949	0.3407	0.3213
P_2	0		0.2465	0.3102	0.2666	0.2608
	1		0.2769	0.2737	0.2621	0.2912
	3		0.3632	0.3195	0.3011	0.3110
	7		0.3096	0.2982	0.3103	0.3060
P_3	0		0.2628	0.2759	0.2296	0.2180
	1		0.2466	0.2469	0.2436	0.2410
	3		0.2580	0.2592	0.2542	0.2522
	7		0.2781	0.2509	0.2602	0.2849

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time L_t_ha
rep.	48	48	48	12
l.s.d.	0.01836	0.02117	0.02117	0.03807
d.f.	81.80	30	30	110.93
Except when comparing means with the same level(s) of L_t_ha				0.03671
d.f.				81.80

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	0.03807	0.04233	0.07613
d.f.	110.93	30	110.93
Except when comparing means with the same level(s) of N_kg_ha			0.03671
d.f.			81.80
L_t_ha.N_kg_ha			0.07342
d.f.			81.80

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: P,P_1,P_2,P_3

Stratum	d.f.	s.e.	cv%
rep	2	0.01573	5.2
rep.Subject	30	0.02539	8.3
rep.Subject.Time	96	0.04397	14.4

Analysis of variance

Variate: S,S_1,S_2,S_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.013103	0.006551	2.17	
rep.Subject stratum					
L_t_ha	3	0.000120	0.000040	0.01	0.998
N_kg_ha	3	0.016833	0.005611	1.86	0.157
L_t_ha.N_kg_ha	9	0.036412	0.004046	1.34	0.258
Residual	30	0.090409	0.003014	0.98	
rep.Subject.Time stratum					
d.f. correction factor 0.7842					
Time	3	0.622376	0.207459	67.14	<.001
Time.L_t_ha	9	0.025786	0.002865	0.93	0.491
Time.N_kg_ha	9	0.076197	0.008466	2.74	0.013
Time.L_t_ha.N_kg_ha	27	0.049385	0.001829	0.59	0.913
Residual	96	0.296637	0.003090		
Total	191	1.227257			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 2 Subject 2	-0.0525	s.e. 0.0217
rep 2 Subject 6	0.0563	s.e. 0.0217
rep 1 Subject 3 Time S	0.1374	s.e. 0.0393
rep 1 Subject 3 Time S_2	-0.1009	s.e. 0.0393
rep 1 Subject 16 Time S	0.1055	s.e. 0.0393
rep 2 Subject 6 Time S_2	0.1163	s.e. 0.0393
rep 3 Subject 15 Time S_3	0.1067	s.e. 0.0393

Tables of means

Variate: S,S_1,S_2,S_3

Grand mean 0.4588

Time	S	S_1	S_2	S_3
	0.5226	0.4233	0.5049	0.3846
L_t_ha	0	1	3	7
	0.4579	0.4585	0.4601	0.4588
N_kg_ha	0	60	120	200
	0.4444	0.4587	0.4703	0.4620

Time	L_t_ha	0	1	3	7
S		0.5234	0.5236	0.5050	0.5386
S_1		0.4293	0.4206	0.4201	0.4232
S_2		0.5094	0.5166	0.5018	0.4916
S_3		0.3696	0.3734	0.4135	0.3818

Time	N_kg_ha	0	60	120	200
S		0.4684	0.5300	0.5369	0.5553
S_1		0.4094	0.4454	0.4151	0.4232
S_2		0.5132	0.4717	0.5414	0.4932
S_3		0.3865	0.3879	0.3877	0.3762

L_t_ha	N_kg_ha	0	60	120	200
0		0.4237	0.4726	0.4561	0.4793
1		0.4454	0.4605	0.4828	0.4454
3		0.4548	0.4689	0.4549	0.4618
7		0.4535	0.4330	0.4873	0.4614

Time	L_t_ha	N_kg_ha	0	60	120	200
S	0		0.4472	0.5580	0.5277	0.5608
	1		0.4827	0.5368	0.5228	0.5520
	3		0.4663	0.5183	0.5134	0.5220
	7		0.4774	0.5070	0.5837	0.5863
S_1	0		0.3806	0.4551	0.4158	0.4657
	1		0.4193	0.4300	0.4341	0.3987
	3		0.4142	0.4427	0.3934	0.4299
	7		0.4235	0.4536	0.4173	0.3986
S_2	0		0.5057	0.4669	0.5314	0.5336
	1		0.5193	0.4988	0.6008	0.4474
	3		0.5067	0.4801	0.5110	0.5096
	7		0.5209	0.4409	0.5223	0.4821
S_3	0		0.3613	0.4104	0.3496	0.3570
	1		0.3603	0.3763	0.3735	0.3836
	3		0.4320	0.4346	0.4017	0.3856
	7		0.3923	0.3304	0.4260	0.3785

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
rep.	48	48	48	L_t_ha
l.s.d.	0.02356	0.02289	0.02289	0.04678
d.f.	75.28	30	30	104.48
Except when comparing means with the same level(s) of L_t_ha				0.04712
d.f.				75.28

Table	Time	L_t_ha	Time	
	N_kg_ha	N_kg_ha	L_t_ha	
rep.	12	12	N_kg_ha	
l.s.d.	0.04678	0.04577	0.09355	
d.f.	104.48	30	104.48	
Except when comparing means with the same level(s) of N_kg_ha			0.09424	
d.f.	75.28			
L_t_ha.N_kg_ha			0.09424	
d.f.				75.28

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: S,S_1,S_2,S_3

Stratum	d.f.	s.e.	cv%
rep	2	0.01012	2.2
rep.Subject	30	0.02745	6.0
rep.Subject.Time	96	0.05559	12.1

Analysis of variance

Variate: Zn,Zn_1,Zn_2,Zn_3 (1st and 2nd leaf sampling over two years)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	1362.3	681.2	0.51	
rep.Subject stratum					
L_t_ha	3	15914.7	5304.9	3.94	0.018
N_kg_ha	3	2208.4	736.1	0.55	0.654
L_t_ha.N_kg_ha	9	10179.9	1131.1	0.84	0.586
Residual	30	40381.0	1346.0	2.27	
rep.Subject.Time stratum					
d.f. correction factor 0.5894					
Time	3	33338.6	11112.9	18.74	<.001
Time.L_t_ha	9	5282.2	586.9	0.99	0.435
Time.N_kg_ha	9	4169.8	463.3	0.78	0.574
Time.L_t_ha.N_kg_ha	27	17351.0	642.6	1.08	0.391
Residual	96	56928.5	593.0		
Total	191	187116.4			

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

rep 1 Subject 1	-33.2	s.e. 14.5
rep 1 Subject 14	39.6	s.e. 14.5
rep 2 Subject 10	32.9	s.e. 14.5
rep 1 Subject 1 Time Zn_3	-53.3	s.e. 17.2
rep 1 Subject 14 Time Zn_2	81.1	s.e. 17.2
rep 2 Subject 5 Time Zn_2	-44.6	s.e. 17.2
rep 2 Subject 8 Time Zn_2	74.0	s.e. 17.2
rep 2 Subject 10 Time Zn_3	82.2	s.e. 17.2

Tables of means

Variate: Zn,Zn_1,Zn_2,Zn_3

Grand mean 71.1

Time	Zn	Zn_1	Zn_2	Zn_3
	56.8	60.0	88.4	79.3

L_t_ha	0	1	3	7
	83.4	74.0	69.0	58.1

N_kg_ha	0	60	120	200
	67.3	70.1	70.6	76.6

Time	L_t_ha	0	1	3	7
Zn		62.6	61.3	55.4	47.9
Zn_1		64.4	62.6	59.8	53.0
Zn_2		109.0	96.3	82.2	66.0
Zn_3		97.4	75.8	78.4	65.7

Time	N_kg_ha	0	60	120	200
Zn		56.4	58.6	56.6	55.7
Zn_1		60.0	60.9	58.8	60.2
Zn_2		75.2	88.1	92.4	97.8
Zn_3		77.4	72.8	74.4	92.6

L_t_ha	N_kg_ha	0	60	120	200
0		72.5	67.9	88.4	104.7
1		72.7	82.9	68.4	72.0
3		67.6	66.1	68.0	74.2
7		56.3	63.4	57.5	55.4

Time	L_t_ha	N_kg_ha	0	60	120	200
Zn	0		53.7	62.9	66.4	67.5
	1		65.4	68.5	57.1	54.4
	3		56.0	57.9	56.5	51.3
	7		50.4	45.1	46.5	49.3
Zn_1	0		61.1	65.2	66.3	65.1
	1		67.2	62.5	58.3	62.4
	3		57.8	60.4	57.5	63.7
	7		54.0	55.3	53.1	49.8
Zn_2	0		92.2	66.6	143.3	133.9
	1		81.2	122.6	83.4	98.1
	3		71.8	69.6	84.2	103.3
	7		55.6	93.8	58.7	55.9
Zn_3	0		82.8	77.1	77.5	152.4
	1		77.1	78.2	74.7	73.0
	3		84.6	76.5	73.9	78.6
	7		65.2	59.3	71.6	66.5

Least significant differences of means (5% level)

Table	Time	L_t_ha	N_kg_ha	Time
rep.	48	48	48	L_t_ha
l.s.d.	10.86	15.29	15.29	24.78
d.f.	56.59	30	30	83.95

Except when comparing means with the same level(s) of
 L_t_ha 21.72
 d.f. 56.59

Table	Time N_kg_ha	L_t_ha N_kg_ha	Time L_t_ha N_kg_ha
rep.	12	12	3
l.s.d.	24.78	30.59	49.56
d.f.	83.95	30	83.95
Except when comparing means with the same level(s) of			
N_kg_ha	21.72		
d.f.	56.59		
L_t_ha.N_kg_ha			43.44
d.f.			56.59

Correction factors have been applied to residual d.f.(see analysis-of-variance table for details)

Stratum standard errors and coefficients of variation

Variate: Zn,Zn_1,Zn_2,Zn_3

Stratum	d.f.	s.e.	cv%
rep	2	3.26	4.6
rep.Subject	30	18.34	25.8
rep.Subject.Time	96	24.35	34.2

Appendix 6.4: Chapter 6 ((NH₄)₂SO₄ and dolomitic lime) root statistical analysis

Analysis of variance

Variate: Al_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	6657.	3328.	0.08	
rep.*Units* stratum					
L_t_ha	3	403318.	134439.	3.11	0.041
Lin	1	283479.	283479.	6.57	0.016
Quad	1	85204.	85204.	1.97	0.170
Deviations	1	34635.	34635.	0.80	0.378
N_kg_ha	3	55682.	18561.	0.43	0.733
Lin	1	3711.	3711.	0.09	0.771
Quad	1	1425.	1425.	0.03	0.857
Deviations	1	50547.	50547.	1.17	0.288
L_t_ha.N_kg_ha	9	449899.	49989.	1.16	0.356
Lin.Lin	1	29301.	29301.	0.68	0.416
Quad.Lin	1	72016.	72016.	1.67	0.206
Lin.Quad	1	23599.	23599.	0.55	0.465
Dev.Lin	1	70042.	70042.	1.62	0.212
Quad.Quad	1	55082.	55082.	1.28	0.268
Lin.Dev	1	63776.	63776.	1.48	0.234
Dev.Quad	1	6233.	6233.	0.14	0.707
Quad.Dev	1	59281.	59281.	1.37	0.250
Deviations	1	70569.	70569.	1.63	0.211

Residual	30	1294902.	43163.
Total	47	2210458.	

Message: the following units have large residuals.

rep 1 *units* 5	376.	s.e. 164.
rep 1 *units* 10	-450.	s.e. 164.
rep 3 *units* 12	526.	s.e. 164.

Tables of means

Variate: AI_4 Root data

Grand mean 682.

L_t_ha	0	1	3	7	
	830.	681.	632.	586.	
N_kg_ha	0	60	120	200	
	704.	644.	726.	654.	
L_t_ha	N_kg_ha	0	60	120	200
0		727.	628.	1101.	865.
1		721.	753.	680.	568.
3		747.	594.	559.	627.
7		622.	602.	565.	557.

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	173.2	173.2	346.4

Stratum standard errors and coefficients of variation

Variate: AI_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	14.4	2.1
rep.*Units*	30	207.8	30.5

Analysis of variance

Variate: B_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	4.1857	2.0929	3.09	
rep.*Units* stratum					

Stratum standard errors and coefficients of variation

Variate: B_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	0.362	5.0
rep.*Units*	30	0.823	11.4

Analysis of variance

Variate: Ca_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.0019605	0.0009802	2.34	
rep.*Units* stratum					
L_t_ha	3	0.0018601	0.0006200	1.48	0.239
Lin	1	0.0007848	0.0007848	1.88	0.181
Quad	1	0.0008727	0.0008727	2.09	0.159
Deviations	1	0.0002026	0.0002026	0.48	0.492
N_kg_ha	3	0.0003221	0.0001074	0.26	0.856
Lin	1	0.0000404	0.0000404	0.10	0.758
Quad	1	0.0000386	0.0000386	0.09	0.763
Deviations	1	0.0002431	0.0002431	0.58	0.452
L_t_ha.N_kg_ha	9	0.0024619	0.0002735	0.65	0.742
Lin.Lin	1	0.0007258	0.0007258	1.74	0.198
Quad.Lin	1	0.0005011	0.0005011	1.20	0.282
Lin.Quad	1	0.0002274	0.0002274	0.54	0.467
Dev.Lin	1	0.0003580	0.0003580	0.86	0.362
Quad.Quad	1	0.0000139	0.0000139	0.03	0.856
Lin.Dev	1	0.0004160	0.0004160	0.99	0.327
Dev.Quad	1	0.0000048	0.0000048	0.01	0.916
Quad.Dev	1	0.0000174	0.0000174	0.04	0.840
Deviations	1	0.0001976	0.0001976	0.47	0.497
Residual	30	0.0125446	0.0004182		
Total	47	0.0191492			

Message: the following units have large residuals.

rep 2 *units* 16	-0.0438	s.e. 0.0162
rep 3 *units* 16	0.0348	s.e. 0.0162

Tables of means

Variate: Ca_4 Root data

Grand mean 0.1607

L_t_ha	0	1	3	7
	0.1539	0.1557	0.1693	0.1640
N_kg_ha	0	60	120	200
	0.1616	0.1563	0.1628	0.1621

L_t_ha	N_kg_ha	0	60	120	200
0		0.1537	0.1419	0.1652	0.1550
1		0.1635	0.1587	0.1558	0.1450
3		0.1731	0.1657	0.1715	0.1668
7		0.1562	0.1590	0.1588	0.1818

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	0.01705	0.01705	0.03410

Stratum standard errors and coefficients of variation

Variate: Ca_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	0.00783	4.9
rep.*Units*	30	0.02045	12.7

Analysis of variance

Variate: Cu_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	48.331	24.165	9.54	
rep.*Units* stratum					
L_t_ha	3	8.531	2.844	1.12	0.355
Lin	1	1.462	1.462	0.58	0.453
Quad	1	7.069	7.069	2.79	0.105
Deviations	1	0.000	0.000	0.00	0.993
N_kg_ha	3	1.689	0.563	0.22	0.880
Lin	1	0.331	0.331	0.13	0.720
Quad	1	1.339	1.339	0.53	0.473
Deviations	1	0.020	0.020	0.01	0.930
L_t_ha.N_kg_ha	9	10.893	1.210	0.48	0.878
Lin.Lin	1	0.074	0.074	0.03	0.866
Quad.Lin	1	0.449	0.449	0.18	0.677
Lin.Quad	1	0.526	0.526	0.21	0.652
Dev.Lin	1	2.393	2.393	0.95	0.339
Quad.Quad	1	0.367	0.367	0.15	0.706
Lin.Dev	1	0.508	0.508	0.20	0.657
Dev.Quad	1	1.232	1.232	0.49	0.491
Quad.Dev	1	0.364	0.364	0.14	0.707
Deviations	1	4.980	4.980	1.97	0.171
Residual	30	75.958	2.532		
Total	47	145.403			

Message: the following units have large residuals.

rep 1 *units* 15

2.98

s.e. 1.26

Tables of means

Variate: Cu_4 Root data

Grand mean 10.52

L_t_ha	0	1	3	7	
	10.30	10.72	11.10	9.98	
N_kg_ha	0	60	120	200	
	10.60	10.31	10.39	10.79	
L_t_ha	N_kg_ha	0	60	120	200
0		10.08	10.02	10.51	10.58
1		11.08	11.32	9.58	10.88
3		10.70	10.37	11.86	11.46
7		10.55	9.54	9.60	10.24

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	1.327	1.327	2.653

Stratum standard errors and coefficients of variation

Variate: Cu_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	1.229	11.7
rep.*Units*	30	1.591	15.1

Analysis of variance

Variate: Fe_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	28953.	14476.	0.44	
rep.*Units* stratum					
L_t_ha	3	272170.	90723.	2.76	0.059
Lin	1	147364.	147364.	4.48	0.043
Quad	1	46648.	46648.	1.42	0.243
Deviations	1	78158.	78158.	2.38	0.134
N_kg_ha	3	41132.	13711.	0.42	0.742
Lin	1	1292.	1292.	0.04	0.844
Quad	1	7817.	7817.	0.24	0.629
Deviations	1	32023.	32023.	0.97	0.332
L_t_ha.N_kg_ha	9	270588.	30065.	0.91	0.526

Lin.Lin	1	25668.	25668.	0.78	0.384
Quad.Lin	1	57358.	57358.	1.74	0.197
Lin.Quad	1	64.	64.	0.00	0.965
Dev.Lin	1	81938.	81938.	2.49	0.125
Quad.Quad	1	64.	64.	0.00	0.965
Lin.Dev	1	19608.	19608.	0.60	0.446
Dev.Quad	1	28755.	28755.	0.87	0.357
Quad.Dev	1	14561.	14561.	0.44	0.511
Deviations	1	42571.	42571.	1.29	0.264
Residual	30	986632.	32888.		
Total	47	1599474.			

Message: the following units have large residuals.

rep 1 *units* 10	-320.	s.e. 143.
rep 2 *units* 10	366.	s.e. 143.
rep 3 *units* 12	433.	s.e. 143.

Tables of means

Variate: Fe_4 Root data

Grand mean 538.

L_t_ha	0	1	3	7	
	664.	503.	517.	467.	
N_kg_ha	0	60	120	200	
	557.	487.	557.	549.	
L_t_ha	N_kg_ha	0	60	120	200
0		617.	451.	772.	816.
1		538.	567.	499.	408.
3		581.	469.	502.	514.
7		493.	461.	455.	457.

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	151.2	151.2	302.4

Stratum standard errors and coefficients of variation

Variate: Fe_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	30.1	5.6
rep.*Units*	30	181.3	33.7

Analysis of variance

Variate: K_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.02608	0.01304	0.43	
rep.*Units* stratum					
L_t_ha	3	0.30696	0.10232	3.37	0.031
Lin	1	0.08988	0.08988	2.96	0.096
Quad	1	0.21226	0.21226	6.99	0.013
Deviations	1	0.00482	0.00482	0.16	0.693
N_kg_ha	3	0.02585	0.00862	0.28	0.837
Lin	1	0.00340	0.00340	0.11	0.740
Quad	1	0.01351	0.01351	0.44	0.510
Deviations	1	0.00895	0.00895	0.29	0.591
L_t_ha.N_kg_ha	9	0.48326	0.05370	1.77	0.117
Lin.Lin	1	0.04867	0.04867	1.60	0.215
Quad.Lin	1	0.06092	0.06092	2.01	0.167
Lin.Quad	1	0.00231	0.00231	0.08	0.785
Dev.Lin	1	0.03375	0.03375	1.11	0.300
Quad.Quad	1	0.04288	0.04288	1.41	0.244
Lin.Dev	1	0.20001	0.20001	6.58	0.016
Dev.Quad	1	0.01165	0.01165	0.38	0.541
Quad.Dev	1	0.01734	0.01734	0.57	0.456
Deviations	1	0.06573	0.06573	2.16	0.152
Residual	30	0.91141	0.03038		
Total	47	1.75355			

Message: the following units have large residuals.

rep 1 *units* 12	-0.344	s.e. 0.138
rep 2 *units* 8	0.342	s.e. 0.138

Tables of means

Variate: K_4 Root data

Grand mean 1.413

L_t_ha	0	1	3	7	
	1.307	1.383	1.527	1.434	
N_kg_ha	0	60	120	200	
	1.434	1.422	1.373	1.421	
L_t_ha	N_kg_ha	0	60	120	200
0		1.449	1.416	1.141	1.221
1		1.342	1.498	1.205	1.485
3		1.472	1.476	1.649	1.511
7		1.473	1.298	1.499	1.467

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	0.1453	0.1453	0.2906

Stratum standard errors and coefficients of variation

Variate: K_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	0.0285	2.0
rep.*Units*	30	0.1743	12.3

Analysis of variance

Variate: Mg_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.0000497	0.0000248	0.14	
rep.*Units* stratum					
L_t_ha	3	0.0000945	0.0000315	0.18	0.908
Lin	1	0.0000211	0.0000211	0.12	0.729
Quad	1	0.0000685	0.0000685	0.40	0.534
Deviations	1	0.0000049	0.0000049	0.03	0.867
N_kg_ha	3	0.0005957	0.0001986	1.15	0.346
Lin	1	0.0001461	0.0001461	0.84	0.366
Quad	1	0.0000570	0.0000570	0.33	0.570
Deviations	1	0.0003926	0.0003926	2.27	0.143
L_t_ha.N_kg_ha	9	0.0007969	0.0000885	0.51	0.854
Lin.Lin	1	0.0003260	0.0003260	1.88	0.180
Quad.Lin	1	0.0000873	0.0000873	0.50	0.483
Lin.Quad	1	0.0000788	0.0000788	0.46	0.505
Dev.Lin	1	0.0001206	0.0001206	0.70	0.410
Quad.Quad	1	0.0000788	0.0000788	0.46	0.505
Lin.Dev	1	0.0000906	0.0000906	0.52	0.475
Dev.Quad	1	0.0000070	0.0000070	0.04	0.841
Quad.Dev	1	0.0000023	0.0000023	0.01	0.909
Deviations	1	0.0000054	0.0000054	0.03	0.862
Residual	30	0.0051931	0.0001731		
Total	47	0.0067298			

Message: the following units have large residuals.

rep 2 *units* 3	-0.0224	s.e. 0.0104
rep 3 *units* 1	0.0275	s.e. 0.0104

Tables of means

Variate: Mg_4 Root data

Grand mean 0.1069

L_t_ha	0	1	3	7	
	0.1066	0.1071	0.1089	0.1050	
N_kg_ha	0	60	120	200	
	0.1044	0.1093	0.1026	0.1113	
L_t_ha	N_kg_ha	0	60	120	200
0		0.1085	0.1078	0.1030	0.1071
1		0.1103	0.1103	0.1014	0.1062
3		0.1043	0.1071	0.1040	0.1203
7		0.0943	0.1118	0.1022	0.1117

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	0.01097	0.01097	0.02194

Stratum standard errors and coefficients of variation

Variate: Mg_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	0.00125	1.2
rep.*Units*	30	0.01316	12.3

Analysis of variance

Variate: Mn_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	210.5	105.2	1.02	
rep.*Units* stratum					
L_t_ha	3	1337.4	445.8	4.34	0.012
Lin	1	1270.1	1270.1	12.37	0.001
Quad	1	4.8	4.8	0.05	0.831
Deviations	1	62.4	62.4	0.61	0.442
N_kg_ha	3	454.2	151.4	1.47	0.241
Lin	1	313.5	313.5	3.05	0.091
Quad	1	136.2	136.2	1.33	0.258
Deviations	1	4.5	4.5	0.04	0.836
L_t_ha.N_kg_ha	9	1451.4	161.3	1.57	0.169
Lin.Lin	1	2.0	2.0	0.02	0.889
Quad.Lin	1	173.6	173.6	1.69	0.203
Lin.Quad	1	23.2	23.2	0.23	0.638

rep stratum	2	2434435.	1217218.	5.97	
rep.*Units* stratum					
L_t_ha	3	2190678.	730226.	3.58	0.025
Lin	1	1365362.	1365362.	6.69	0.015
Quad	1	773099.	773099.	3.79	0.061
Deviations	1	52218.	52218.	0.26	0.617
N_kg_ha	3	90321.	30107.	0.15	0.930
Lin	1	16652.	16652.	0.08	0.777
Quad	1	1415.	1415.	0.01	0.934
Deviations	1	72254.	72254.	0.35	0.556
L_t_ha.N_kg_ha	9	1760657.	195629.	0.96	0.492
Lin.Lin	1	477712.	477712.	2.34	0.136
Quad.Lin	1	123961.	123961.	0.61	0.442
Lin.Quad	1	43478.	43478.	0.21	0.648
Dev.Lin	1	198212.	198212.	0.97	0.332
Quad.Quad	1	113765.	113765.	0.56	0.461
Lin.Dev	1	192388.	192388.	0.94	0.339
Dev.Quad	1	10454.	10454.	0.05	0.822
Quad.Dev	1	584595.	584595.	2.87	0.101
Deviations	1	16093.	16093.	0.08	0.781
Residual	30	6120747.	204025.		
Total	47	12596839.			

Message: the following units have large residuals.

rep 1 *units* 16	-847.	s.e. 357.
rep 2 *units* 7	904.	s.e. 357.

Tables of means

Variate: Na_4 Root data

Grand mean 3358.

L_t_ha	0	1	3	7	
	3635.	3493.	3121.	3181.	
N_kg_ha	0	60	120	200	
	3407.	3306.	3394.	3324.	
L_t_ha	N_kg_ha	0	60	120	200
0		3767.	3642.	3758.	3373.
1		3456.	3508.	3531.	3477.
3		3328.	3306.	2790.	3058.
7		3076.	2768.	3495.	3386.

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	376.6	376.6	753.2

Stratum standard errors and coefficients of variation

Variate: Na_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	275.8	8.2
rep.*Units*	30	451.7	13.5

Analysis of variance

Variate: N_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.04764	0.02382	0.72	
rep.*Units* stratum					
L_t_ha	3	0.09987	0.03329	1.01	0.401
Lin	1	0.00260	0.00260	0.08	0.781
Quad	1	0.08476	0.08476	2.58	0.119
Deviations	1	0.01251	0.01251	0.38	0.542
N_kg_ha	3	0.06616	0.02205	0.67	0.576
Lin	1	0.04827	0.04827	1.47	0.235
Quad	1	0.01382	0.01382	0.42	0.522
Deviations	1	0.00406	0.00406	0.12	0.728
L_t_ha.N_kg_ha	9	0.14443	0.01605	0.49	0.871
Lin.Lin	1	0.01137	0.01137	0.35	0.561
Quad.Lin	1	0.02512	0.02512	0.76	0.389
Lin.Quad	1	0.04793	0.04793	1.46	0.237
Dev.Lin	1	0.00826	0.00826	0.25	0.620
Quad.Quad	1	0.00888	0.00888	0.27	0.607
Lin.Dev	1	0.00669	0.00669	0.20	0.655
Dev.Quad	1	0.00333	0.00333	0.10	0.753
Quad.Dev	1	0.03254	0.03254	0.99	0.328
Deviations	1	0.00031	0.00031	0.01	0.923
Residual	30	0.98570	0.03286		
Total	47	1.34379			

Message: the following units have large residuals.

rep 1 *units* 1	0.368	s.e.	0.143
rep 3 *units* 11	-0.463	s.e.	0.143
rep 3 *units* 16	0.366	s.e.	0.143

Tables of means

Variate: N_4 Root data

Grand mean 0.815

L_t_ha	0	1	3	7
	0.778	0.794	0.894	0.796
N_kg_ha	0	60	120	200
	0.788	0.799	0.795	0.879

L_t_ha	N_kg_ha	0	60	120	200
0		0.779	0.820	0.689	0.824
1		0.835	0.768	0.715	0.857
3		0.839	0.784	0.930	1.021
7		0.699	0.826	0.846	0.815

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	0.1511	0.1511	0.3023

Stratum standard errors and coefficients of variation

Variate: N_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	0.0386	4.7
rep.*Units*	30	0.1813	22.2

Analysis of variance

Variate: P_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	0.0083919	0.0041960	4.56	
rep.*Units* stratum					
L_t_ha	3	0.0071049	0.0023683	2.57	0.073
Lin	1	0.0022496	0.0022496	2.44	0.129
Quad	1	0.0043071	0.0043071	4.68	0.039
Deviations	1	0.0005481	0.0005481	0.60	0.446
N_kg_ha	3	0.0021609	0.0007203	0.78	0.513
Lin	1	0.0000009	0.0000009	0.00	0.975
Quad	1	0.0014119	0.0014119	1.53	0.225
Deviations	1	0.0007480	0.0007480	0.81	0.375
L_t_ha.N_kg_ha	9	0.0060709	0.0006745	0.73	0.676
Lin.Lin	1	0.0022198	0.0022198	2.41	0.131
Quad.Lin	1	0.0008323	0.0008323	0.90	0.349
Lin.Quad	1	0.0004721	0.0004721	0.51	0.480
Dev.Lin	1	0.0007622	0.0007622	0.83	0.370
Quad.Quad	1	0.0000001	0.0000001	0.00	0.991
Lin.Dev	1	0.0010001	0.0010001	1.09	0.306
Dev.Quad	1	0.0000471	0.0000471	0.05	0.823
Quad.Dev	1	0.0000893	0.0000893	0.10	0.758
Deviations	1	0.0006480	0.0006480	0.70	0.408
Residual	30	0.0276295	0.0009210		
Total	47	0.0513582			

Analysis of variance

Variate: Zn_4 Root data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
rep stratum	2	95.78	47.89	1.35	
rep.*Units* stratum					
L_t_ha	3	306.79	102.26	2.88	0.052
Lin	1	247.51	247.51	6.97	0.013
Quad	1	38.90	38.90	1.10	0.304
Deviations	1	20.38	20.38	0.57	0.455
N_kg_ha	3	30.85	10.28	0.29	0.832
Lin	1	1.11	1.11	0.03	0.861
Quad	1	29.74	29.74	0.84	0.367
Deviations	1	0.00	0.00	0.00	0.994
L_t_ha.N_kg_ha	9	163.37	18.15	0.51	0.855
Lin.Lin	1	32.70	32.70	0.92	0.345
Quad.Lin	1	12.40	12.40	0.35	0.559
Lin.Quad	1	1.51	1.51	0.04	0.838
Dev.Lin	1	35.09	35.09	0.99	0.328
Quad.Quad	1	11.03	11.03	0.31	0.581
Lin.Dev	1	10.91	10.91	0.31	0.583
Dev.Quad	1	1.09	1.09	0.03	0.862
Quad.Dev	1	56.68	56.68	1.60	0.216
Deviations	1	1.95	1.95	0.05	0.816
Residual	30	1064.96	35.50		
Total	47	1661.75			

Message: the following units have large residuals.

rep 1 *units* 8	-12.43	s.e. 4.71
rep 1 *units* 11	10.94	s.e. 4.71

Tables of means

Variate: Zn_4 Root data

Grand mean 28.83

L_t_ha	0	1	3	7	
	30.80	29.47	30.52	24.54	
N_kg_ha	0	60	120	200	
	29.46	28.10	27.98	29.79	
L_t_ha	N_kg_ha	0	60	120	200
0		30.77	31.77	26.87	33.79
1		32.55	29.54	28.49	27.29
3		31.29	28.11	32.33	30.35
7		23.21	23.00	24.21	27.73

Least significant differences of means (5% level)

Table	L_t_ha	N_kg_ha	L_t_ha N_kg_ha
rep.	12	12	3
d.f.	30	30	30
l.s.d.	4.968	4.968	9.935

Stratum standard errors and coefficients of variation

Variate: Zn_4 Root data

Stratum	d.f.	s.e.	cv%
rep	2	1.730	6.0
rep.*Units*	30	5.958	20.7

Appendix 7.1: X-ray diffraction analysis

The mineralogical composition of the clay fraction was characterised using X-ray diffraction (XRD) on oriented specimens. The clay fraction (<2 µm) was obtained from the soil by using sedimentation flasks and applying Stokes' Law. Prior to preparation of the oriented specimens on glass slides, about two thirds of the separated clay fraction was saturated with Mg²⁺ and one third with K⁺. Three oriented specimen glass slides were then prepared with the Mg-saturated clay and two oriented specimen glass slides with the potassium saturated clay. The three Mg-saturated specimens were air-dried, treated with ethylene glycol at 60°C overnight and treated with glycerol at 85°C overnight, respectively, and the two K saturated specimens were air-dried and heated at 550°C for four hours, respectively (Bühmann et al., 1985). X-ray diffraction analysis was carried out using a Philips PW1050 X-ray diffractometer fitted with a Philips PW1170 automatic sample changer and a graphite monochromator at 40 kV and 40 mA using CoK α radiation. The oriented specimens were scanned at 1° min⁻¹ with a step-scan of 0.02° between 3 and 45° 2 Θ . A Sietronics SIE122D automated interface unit running Sietronics X-ray analytical software V2.6 was used to capture the X-ray data, whilst Sietronics XRD Traces processing software V2.0 was used to analyse the traces captured.

Appendix 7.2: X-ray fluorescence analysis

Major elements were analysed using lithium borate-fused discs on a Philips PW 1410 wavelength dispersive X-ray fluorescence spectrometer at 50 kV and 50 mA. Certified reference materials were used as calibration standards throughout the analyses (Govindaraju, 1994).

Appendix 7.3: X-ray fluorescence analysis (%) of the five soil types (0-30 cm)

Soil	Loss on Ignition	Sum of conc.	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	V ₂ O ₅	Cr ₂ O ₃	SrO	ZrO ₂	BaO	NiO	CuO	ZnO	
DARS	3.68	99.21	92.98	0.55	3.51	1.24	0.01	0.06	0.05	0	0.60	0.06	0.02	0.01	0.01	0	0.11	0.01	0	0	0	
Ruigtefontein	0.48	99.64	95.36	0.08	1.81	0.48	0.03	0.11	0.20	0.15	0.92	0.02	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Nkaseni	13.52	99.47	66.66	1.20	15.39	8.20	0.15	1.74	2.28	2.01	1.53	0.07	0.04	0.03	0.02	0.02	0.05	0.07	0.01	0.01	0.01	
Bloukrans	13.75	99.53	63.86	1.05	18.08	8.71	0.15	1.89	2.04	1.15	2.17	0.18	0.02	0.03	0.02	0.01	0.03	0.07	0.01	0.01	0.02	
Sun Valley	7.81	99.32	64.70	1.12	17.36	7.54	0.10	1.66	1.84	1.74	2.88	0.17	0.02	0.03	0.01	0.02	0.03	0.08	0.01	0.01	0.02	

bdl - below detection limit

Appendix 7.4: Mean (n=3) irrigation water quality used in the pot experiment

EC ¹ (mS m ⁻¹)	pH	Cations				Anions		SAR ²	TDS ³	Class of water ⁴
		Na	Ca	Mg	K	Total alkalinity	Cl			
9.46	7.63	0.24	0.46	0.25	0.03	0.5	0.5	0.40	57.71	C1-S1

¹Electrical conductivity; ²Sodium Adsorption Ratio, ³Total Dissolved Solutes, ⁴United States Salinity Laboratory Staff (USSLS) (1954)

Appendix 7.5: Chapter 7 (K pot trial) yield statistical analysis

Analysis of variance

Variate: Leaf_mass_wet_g

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	883.5	441.7	0.72	
Block.*Units* stratum					
Clay	4	38064.4	9516.1	15.60	<.001
Potassium	5	9575.5	1915.1	3.14	0.014
Clay.Potassium	20	8842.4	442.1	0.72	0.784
Residual	58	35369.8	609.8		
Total	89	92735.6			

Message: the following units have large residuals.

Block 2 *units* 2	48.7	s.e. 19.8
Block 2 *units* 8	-60.0	s.e. 19.8
Block 3 *units* 1	52.9	s.e. 19.8
Block 3 *units* 23	-49.5	s.e. 19.8

Tables of means

Variate: Leaf_mass_wet_g

Grand mean 104.6

Clay	Kalonite; 3% clay	Kalonite; 9% clay	Illite; 27% clay
	74.5	96.9	102.3
Clay	Smectite; 36% clay	Mixed; 49% clay	
	137.7	111.6	
Potassium	0	50	100
	95.3	95.7	94.1
		150	200
		114.6	107.1
		250	120.6
	Clay	Potassium	0
	Kalonite; 3% clay		50
			100
			150
			200
			52.7
			70.0
			80.8
			83.9
			80.3

Kalonite; 9% clay	81.9	84.1	87.9	104.7	88.1
Illite; 27% clay	96.5	89.3	90.7	108.4	115.4
Smectite; 36% clay	124.0	122.3	130.0	157.8	129.5
Mixed; 49% clay	121.4	113.0	81.0	118.4	122.3
Clay Potassium	250				
Kalonite; 3% clay	79.2				
Kalonite; 9% clay	134.6				
Illite; 27% clay	113.5				
Smectite; 36% clay	162.4				
Mixed; 49% clay	113.4				

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	16.48	18.05	40.36

Stratum standard errors and coefficients of variation

Variate: Leaf_mass_wet_g

Stratum	d.f.	s.e.	cv%
Block	2	3.84	3.7
Block.*Units*	58	24.69	23.6

Fisher's unprotected least significant difference test

Clay

	Mean	
Kalonite; 3% clay	74.5	a
Kalonite; 9% clay	96.9	b
Illite; 27% clay	102.3	b
Mixed; 49% clay	111.6	b
Smectite; 36% clay	137.7	c

Analysis of variance

Variate: Root_Length_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	39.818	19.909	2.05	
Block.*Units* stratum					
Clay	4	292.419	73.105	7.51	<.001
Potassium	5	23.326	4.665	0.48	0.790
Clay.Potassium	20	124.134	6.207	0.64	0.867

Residual	58	564.615	9.735
Total	89	1044.311	

Message: the following units have large residuals.

Block 2 *units* 4 -7.56 s.e. 2.50

Tables of means

Variate: Root_Length_cm

Grand mean 20.29

Clay	Kalonite; 3% clay	Kalonite; 9% clay	Illite; 27% clay				
	23.47	18.86	20.75				
Clay	Smectite; 36% clay	Mixed; 49% clay					
	20.04	18.34					
Potassium	0	50	100	150	200	250	
	19.99	21.17	20.52	20.54	19.64	19.90	
	Clay	Potassium	0	50	100	150	200
	Kalonite; 3% clay		23.63	23.43	22.70	23.70	23.25
	Kalonite; 9% clay		21.00	18.97	20.17	17.03	17.60
	Illite; 27% clay		19.30	22.17	20.60	21.33	19.17
	Smectite; 36% clay		17.77	23.60	20.02	20.57	19.60
	Mixed; 49% clay		18.23	17.67	19.10	20.08	18.57
	Clay	Potassium	250				
	Kalonite; 3% clay		24.10				
	Kalonite; 9% clay		18.40				
	Illite; 27% clay		21.95				
	Smectite; 36% clay		18.68				
	Mixed; 49% clay		16.37				

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	2.082	2.281	5.099

Stratum standard errors and coefficients of variation

Variate: Root_Length_cm

Stratum	d.f.	s.e.	cv%
Block	2	0.815	4.0
Block.*Units*	58	3.120	15.4

Fisher's unprotected least significant difference test

Clay

	Mean	
Mixed; 49% clay	18.34	a
Kalonite; 9% clay	18.86	ab
Smectite; 36% clay	20.04	ab
Illite; 27% clay	20.75	b
Kalonite; 3% clay	23.47	c

Analysis of variance

Variate: Root_mass_wet_g

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	18196.	9098.	3.17	
Block.*Units* stratum					
Clay	4	121414.	30354.	10.59	<.001
Potassium	5	11895.	2379.	0.83	0.534
Clay.Potassium	20	30356.	1518.	0.53	0.942
Residual	58	166239.	2866.		
Total	89	348100.			

Tables of means

Variate: Root_mass_wet_g

Grand mean 207.6

Clay	Kalonite; 3% clay	Kalonite; 9% clay	Illite; 27% clay				
	169.8	182.5	202.2				
Clay	Smectite; 36% clay	Mixed; 49% clay					
	275.8	207.5					
Potassium	0	50	100	150	200	250	
	198.9	199.3	193.0	209.7	222.9	221.7	
	Clay	Potassium	0	50	100	150	200
	Kalonite; 3% clay		127.7	158.3	160.0	195.0	194.3
	Kalonite; 9% clay		200.0	185.0	155.0	166.7	200.0
	Illite; 27% clay		183.3	211.7	208.3	185.0	190.0
	Smectite; 36% clay		258.3	275.0	235.0	303.3	283.3
	Mixed; 49% clay		225.0	166.7	206.7	198.3	246.7
	Clay	Potassium	250				
	Kalonite; 3% clay		183.3				
	Kalonite; 9% clay		188.3				
	Illite; 27% clay		235.0				
	Smectite; 36% clay		300.0				

Mixed; 49% clay

201.7

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	35.72	39.13	87.50

Stratum standard errors and coefficients of variation

Variate: Root_mass_wet_g

Stratum	d.f.	s.e.	cv%
Block	2	17.41	8.4
Block.*Units*	58	53.54	25.8

Fisher's unprotected least significant difference test

Clay

	Mean	
Kalonite; 3% clay	169.8	a
Kalonite; 9% clay	182.5	ab
Illite; 27% clay	202.2	ab
Mixed; 49% clay	207.5	b
Smectite; 36% clay	275.8	c

Analysis of variance

Variate: Root_width_mm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	208.50	104.25	2.26	
Block.*Units* stratum					
Clay	4	1063.51	265.88	5.76	<.001
Potassium	5	219.45	43.89	0.95	0.455
Clay.Potassium	20	741.73	37.09	0.80	0.699
Residual	58	2676.51	46.15		
Total	89	4909.70			

Message: the following units have large residuals.

Block 1 *units* 24	18.20	s.e. 5.45
Block 2 *units* 4	-13.58	s.e. 5.45
Block 2 *units* 11	-13.31	s.e. 5.45
Block 2 *units* 22	13.02	s.e. 5.45

Tables of means

Variate: Root_width_mm

Grand mean 27.97

Clay	Kalonite; 3% clay		Kalonite; 9% clay		Illite; 27% clay		
	24.78		30.06		28.91		
Clay	Smectite; 36% clay		Mixed; 49% clay				
	32.73		23.39				
Potassium	0	50	100	150	200	250	
	25.26	27.90	29.98	29.26	28.57	26.88	
	Clay	Potassium	0	50	100	150	200
	Kalonite; 3% clay		19.30	25.60	25.50	27.60	23.93
	Kalonite; 9% clay		35.83	31.07	33.83	23.37	29.53
	Illite; 27% clay		23.20	26.93	32.87	29.43	31.43
	Smectite; 36% clay		27.53	34.67	32.53	36.97	33.20
	Mixed; 49% clay		20.42	21.25	25.17	28.93	24.77
	Clay	Potassium	250				
	Kalonite; 3% clay		26.77				
	Kalonite; 9% clay		26.73				
	Illite; 27% clay		29.58				
	Smectite; 36% clay		31.50				
	Mixed; 49% clay		19.80				

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	4.533	4.965	11.103

Stratum standard errors and coefficients of variation

Variate: Root_width_mm

Stratum	d.f.	s.e.	cv%
Block	2	1.864	6.7
Block.*Units*	58	6.793	24.3

Appendix 7.6: Chapter 7 (K pot trial) soil statistical analysis

Analysis of variance

Variate: K_soil_mg_L_final_after_chicory_

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	26325.	13162.	2.37	

Block.*Units* stratum					
Clay	4	1024676.	256169.	46.20	<.001
Potassium	5	128814.	25763.	4.65	0.001
Clay.Potassium	20	178574.	8929.	1.61	0.081
Residual	58	321615.	5545.		
Total	89	1680004.			

Message: the following units have large residuals.

Block 2 *units* 6	-171.7	s.e. 59.8
Block 3 *units* 3	200.2	s.e. 59.8
Block 3 *units* 19	-214.8	s.e. 59.8

Tables of means

Variate: K_soil_mg_L_final_after_chicory_

Grand mean 185.7

Clay	Kalonite; 3% clay 26.7	Kalonite; 9% clay 91.4	Illite; 27% clay 291.9				
Clay	Smectite; 36% clay 240.9	Mixed; 49% clay 277.4					
Potassium	0 127.9	50 169.4	100 158.7	150 195.4	200 229.7	250 232.9	
	Clay	Potassium	0	50	100	150	200
	Kalonite; 3% clay		16.3	23.0	24.7	31.0	31.3
	Kalonite; 9% clay		50.7	76.7	95.0	64.0	134.3
	Illite; 27% clay		198.7	235.3	259.3	393.0	393.3
	Smectite; 36% clay		182.7	164.0	238.0	241.7	240.0
	Mixed; 49% clay		191.3	348.0	176.7	247.3	349.7
	Clay	Potassium	250				
	Kalonite; 3% clay		33.7				
	Kalonite; 9% clay		128.0				
	Illite; 27% clay		272.0				
	Smectite; 36% clay		379.0				
	Mixed; 49% clay		351.7				

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	49.69	54.43	121.71

Stratum standard errors and coefficients of variation

Variate: K_soil_mg_L_final_after_chicory_

Stratum	d.f.	s.e.	cv%
Block	2	20.95	11.3
Block.*Units*	58	74.47	40.1

Fisher's unprotected least significant difference test

Clay

	Mean	
Kalonite; 3% clay	26.7	a
Kalonite; 9% clay	91.4	b
Smectite; 36% clay	240.9	c
Mixed; 49% clay	277.4	cd
Illite; 27% clay	291.9	d

Appendix 7.7: Calculation of total plant removal of potassium (K) for K pot trial using Dundee Agricultural Research Station (DARS) soil as an example

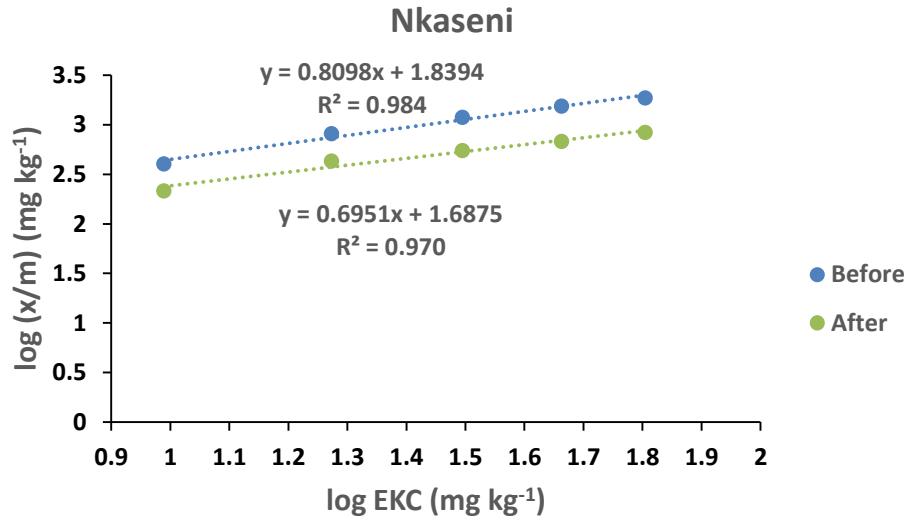
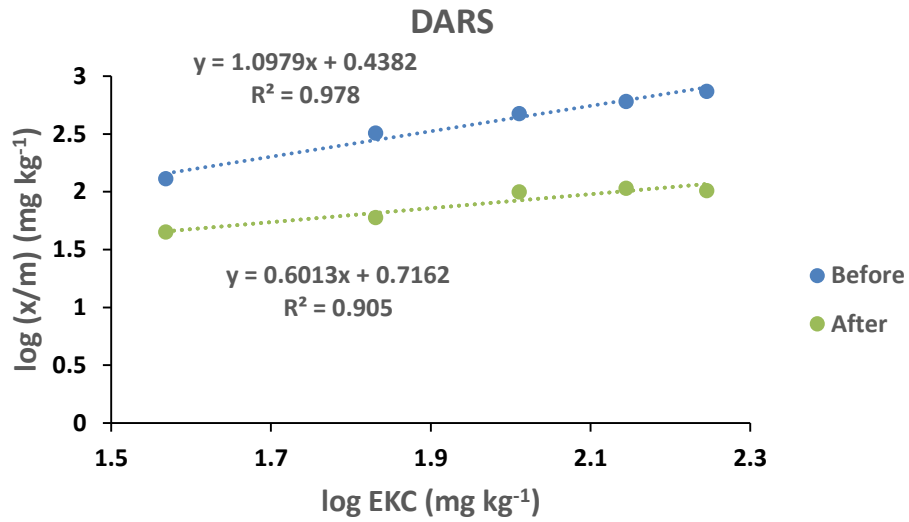
Weighted mean: Leaf K% * DM (g) / moisture (%) + Root K(%) * DM (g) / moisture (%)

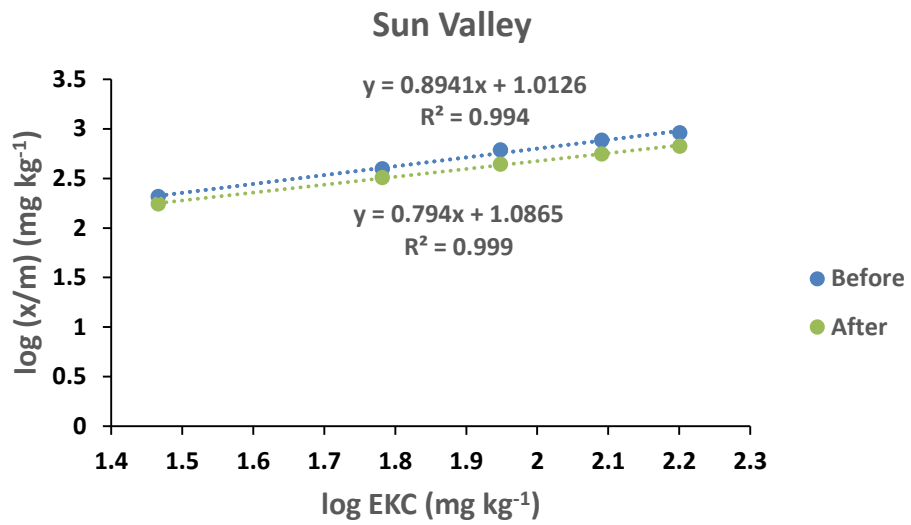
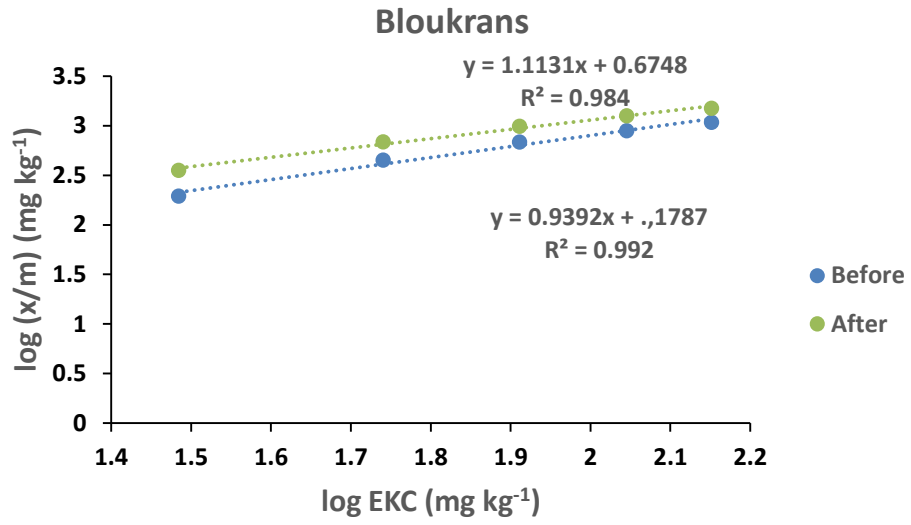
$$= 2.02 * 21.1 / 84.2 + 0.99 * 50.9 / 74.55 = 1.18\% \text{ K}$$

Appendix 7.8: Langmuir and Temkin adsorption isotherm equations for five different soils before experimentation and after chicory harvest

Dominant clay	Equations (before)	R² (before)	Equations (after)	R² (after)
Kaolinite/illite	Langmuir: $y = -0.0002x + 0.2558$	0.129	Langmuir: $y = 0.0059x + 0.776$	0.857
	Temkin: $y = 383.36x - 1275.6$	0.988	Temkin: $y = 40.814x - 113.11$	0.878
Kaolinite	NA	NA	Langmuir: $y = 0.0087x + 6.3606$	0.009
			Temkin: $y = 5.9338x + 4.2901$	0.028
Smectite	Langmuir: $y = -0.0002x + 0.2558$	0.129	Langmuir : $y = 0.0006x + 0.1128$	0.921
	Temkin: $y = 773.27x - 1411.5$	0.991	Temkin: $y = 330.71x - 909.92$	0.971
Mixed layer	Langmuir : $y = -0.0002x + 0.1441$	0.221	Langmuir: $y = 0.0003x + 0.0362$	1.00
	Temkin: $y = 574.8x - 1809.9$	0.986	Temkin: $y = 590.72x - 1282.3$	0.983
Illite	Langmuir: $y = 0.0002x + 0.1333$	0.810	Langmuir: $y = 0.0006x + 0.1702$	0.980
	Temkin: $y = 420.48x - 1258.2$	0.971	Temkin: $y = 278.12x - 821.4$	0.970

Appendix 7.9: Examples of individual Freundlich potassium adsorption isotherms of four soils before experimentation and after chicory harvest





Appendix 7.10: Chapter 7 (K pot trial) leaf statistical analysis

Analysis of variance

Variate: K%_Leaf1_60DAS

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4.6403	2.3202	6.88	
Block.*Units* stratum					
Clay	4	46.3871	11.5968	34.40	<.001
Potassium	5	19.2720	3.8544	11.43	<.001
Clay.Potassium	20	15.6391	0.7820	2.32	0.007
Residual	58	19.5528	0.3371		
Total	89	105.4913			

Message: the following units have large residuals.

Block 3 *units* 1	-1.277	s.e. 0.466
Block 3 *units* 22	1.565	s.e. 0.466

Tables of means

Variate: K%_Leaf1_60DAS

Grand mean 4.199

Clay	Kalonite; 3% clay	Kalonite; 9% clay	Illite; 27% clay			
	4.211	3.226	4.957			
Clay	Smectite; 36% clay	Mixed; 49% clay				
	5.020	3.581				
Potassium	0	50	100	150	200	250
	3.414	3.745	4.301	4.692	4.502	4.542
Clay	Potassium	0	50	100	150	200
Kalonite; 3% clay		2.620	3.230	4.041	4.618	5.382
Kalonite; 9% clay		2.583	2.729	2.916	4.121	3.898
Illite; 27% clay		3.955	4.803	5.642	5.413	4.578
Smectite; 36% clay		4.619	4.691	5.132	5.758	4.999
Mixed; 49% clay		3.291	3.274	3.772	3.549	3.652
Clay	Potassium	250				
Kalonite; 3% clay		5.378				
Kalonite; 9% clay		3.112				
Illite; 27% clay		5.350				
Smectite; 36% clay		4.921				
Mixed; 49% clay		3.946				

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	0.3874	0.4244	0.9490

Stratum standard errors and coefficients of variation

Variate: K%_Leaf1_60DAS

Stratum	d.f.	s.e.	cv%
Block	2	0.2781	6.6
Block.*Units*	58	0.5806	13.8

Fisher's unprotected least significant difference test

Clay

	Mean	
Kalonite; 9% clay	3.226	a
Mixed; 49% clay	3.581	a
Kalonite; 3% clay	4.211	b
Illite; 27% clay	4.957	c
Smectite; 36% clay	5.020	c

Analysis of variance

Variate: K%_Leaf2_DAS_120

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.9419	0.9710	1.15	
Block.*Units* stratum					
Clay	4	61.8555	15.4639	18.38	<.001
Potassium	5	19.3458	3.8692	4.60	0.001
Clay.Potassium	20	10.7257	0.5363	0.64	0.867
Residual	58	48.8051	0.8415		
Total	89	142.6740			

Message: the following units have large residuals.

Block 1 *units* 16	3.540	s.e. 0.736
Block 1 *units* 24	-2.137	s.e. 0.736
Block 3 *units* 20	2.755	s.e. 0.736
Block 3 *units* 21	-1.855	s.e. 0.736

Tables of means

Variate: K%_Leaf2_DAS_120

Grand mean 4.562

Clay	Kalonite; 3% clay	Kalonite; 9% clay	Illite; 27% clay			
	4.321	3.611	5.462			
Clay	Smectite; 36% clay	Mixed; 49% clay				
	5.608	3.807				
Potassium	0	50	100	150	200	250
	3.953	4.127	4.315	4.973	5.239	4.765
Clay	Potassium	0	50	100	150	200
Kalonite; 3% clay		4.006	3.678	3.906	4.501	5.193
Kalonite; 9% clay		2.655	3.597	3.813	3.785	3.867
Illite; 27% clay		5.003	5.205	5.362	5.617	5.854
Smectite; 36% clay		4.881	4.774	4.660	6.859	7.074
Mixed; 49% clay		3.219	3.380	3.835	4.103	4.207
Clay	Potassium	250				
Kalonite; 3% clay		4.641				
Kalonite; 9% clay		3.952				
Illite; 27% clay		5.732				
Smectite; 36% clay		5.401				
Mixed; 49% clay		4.099				

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	0.6121	0.6705	1.4993

Stratum standard errors and coefficients of variation

Variate: K%_Leaf2_DAS_120

Stratum	d.f.	s.e.	cv%
Block	2	0.1799	3.9
Block.*Units*	58	0.9173	20.1

Analysis of variance

Variate: K%_Leaf3_DAS_180

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	3.0549	1.5275	3.29	
Block.*Units* stratum					
Clay	4	76.0275	19.0069	40.96	<.001
Potassium	5	5.4574	1.0915	2.35	0.052
Clay.Potassium	20	10.1196	0.5060	1.09	0.384
Residual	58	26.9113	0.4640		
Total	89	121.5707			

Message: the following units have large residuals.

Block 1 *units* 2	-1.721	s.e. 0.547
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Tables of means

Variate: K%_Leaf3_DAS_180

Grand mean 3.508

Clay	Kalonite; 3% clay 2.352	Kalonite; 9% clay 2.826	Illite; 27% clay 4.709			
Clay	Smectite; 36% clay 4.449	Mixed; 49% clay 3.201				
Potassium	0 3.157	50 3.370	100 3.317	150 3.766	200 3.598	250 3.840
Clay	Potassium	0	50	100	150	200
Kalonite; 3% clay		1.594	1.821	2.128	2.641	2.867
Kalonite; 9% clay		2.019	2.993	2.458	3.090	2.942
Illite; 27% clay		4.976	4.338	4.263	4.775	4.983
Smectite; 36% clay		4.076	4.598	4.463	4.916	4.692
Mixed; 49% clay		3.119	3.098	3.274	3.408	2.504
Clay	Potassium	250				
Kalonite; 3% clay		3.064				
Kalonite; 9% clay		3.459				
Illite; 27% clay		4.920				
Smectite; 36% clay		3.953				
Mixed; 49% clay		3.805				

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	0.4545	0.4979	1.1133

Stratum standard errors and coefficients of variation

Variate: K%_Leaf3_DAS_180

Stratum	d.f.	s.e.	cv%
Block	2	0.2256	6.4
Block.*Units*	58	0.6812	19.4

Fisher's unprotected least significant difference test

Clay

	Mean	
Kalonite; 3% clay	2.352	a
Kalonite; 9% clay	2.826	b
Mixed; 49% clay	3.201	b
Smectite; 36% clay	4.449	c
Illite; 27% clay	4.709	c

Analysis of variance

Variate: K%_Leaf1_60DAS,K%_Leaf2_DAS_120,K%_Leaf3_DAS_180

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	8.6927	4.3464	5.85	
Block.Subject stratum					
Clay	4	165.5308	41.3827	55.72	<.001
Potassium	5	37.3948	7.4790	10.07	<.001
Clay.Potassium	20	17.2901	0.8645	1.16	0.317
Residual	58	43.0737	0.7427	1.68	
Block.Subject.Time stratum					
d.f. correction factor 0.8549					
Time	2	51.6255	25.8127	58.29	<.001
Time.Clay	8	18.7394	2.3424	5.29	<.001
Time.Potassium	10	6.6803	0.6680	1.51	0.159
Time.Clay.Potassium	40	19.1943	0.4799	1.08	0.369
Residual	120	53.1400	0.4428		

Total 269 421.3616

(d.f. are multiplied by the correction factors before calculating F probabilities)

Information summary

All terms orthogonal, none aliased.

Message: the following units have large residuals.

Block 1 Subject 16	0.960	s.e. 0.399
Block 2 Subject 19	1.005	s.e. 0.399
Block 3 Subject 20	1.036	s.e. 0.399
Block 1 Subject 16 Time K%_Leaf2_DAS_120	2.630	s.e. 0.444
Block 1 Subject 16 Time K%_Leaf3_DAS_180	-1.599	s.e. 0.444
Block 2 Subject 16 Time K%_Leaf2_DAS_120	-1.399	s.e. 0.444
Block 3 Subject 20 Time K%_Leaf1_60DAS	-1.186	s.e. 0.444
Block 3 Subject 20 Time K%_Leaf2_DAS_120	1.781	s.e. 0.444
Block 3 Subject 21 Time K%_Leaf2_DAS_120	-1.232	s.e. 0.444

Tables of means

Variate: K%_Leaf1_60DAS,K%_Leaf2_DAS_120,K%_Leaf3_DAS_180

Grand mean 4.090

Time	K%_Leaf1_60DAS	K%_Leaf2_DAS_120	K%_Leaf3_DAS_180			
	4.199	4.562	3.508			
Clay	Kalonite; 3% clay	Kalonite; 9% clay	Illite; 27% clay			
	3.628	3.221	5.043			
Clay	Smectite; 36% clay	Mixed; 49% clay				
	5.026	3.530				
Potassium	0	50	100	150	200	250
	3.508	3.747	3.978	4.477	4.446	4.382
Time	Clay	Kalonite; 3% clay	Kalonite; 9% clay			
K%_Leaf1_60DAS		4.211	3.226			
K%_Leaf2_DAS_120		4.321	3.611			
K%_Leaf3_DAS_180		2.352	2.826			
Time	Clay	Illite; 27% clay	Smectite; 36% clay			
K%_Leaf1_60DAS		4.957	5.020			
K%_Leaf2_DAS_120		5.462	5.608			
K%_Leaf3_DAS_180		4.709	4.449			
Time	Clay	Mixed; 49% clay				
K%_Leaf1_60DAS		3.581				

K%_Leaf2_DAS_120			3.807			
K%_Leaf3_DAS_180			3.201			
Time	Potassium	0	50	100	150	200
K%_Leaf1_60DAS		3.414	3.745	4.301	4.692	4.502
K%_Leaf2_DAS_120		3.953	4.127	4.315	4.973	5.239
K%_Leaf3_DAS_180		3.157	3.370	3.317	3.766	3.598
Time	Potassium	250				
K%_Leaf1_60DAS		4.542				
K%_Leaf2_DAS_120		4.765				
K%_Leaf3_DAS_180		3.840				
Clay	Potassium	0	50	100	150	
Kalonite; 3% clay		2.740	2.910	3.358	3.920	
Kalonite; 9% clay		2.419	3.106	3.062	3.665	
Illite; 27% clay		4.645	4.782	5.089	5.268	
Smectite; 36% clay		4.525	4.688	4.752	5.844	
Mixed; 49% clay		3.210	3.251	3.627	3.687	
Clay	Potassium	200	250			
Kalonite; 3% clay		4.481	4.361			
Kalonite; 9% clay		3.569	3.508			
Illite; 27% clay		5.138	5.334			
Smectite; 36% clay		5.588	4.759			
Mixed; 49% clay		3.455	3.950			
Time	Clay	Potassium	0	50		
K%_Leaf1_60DAS	Kalonite; 3% clay		2.620	3.230		
	Kalonite; 9% clay		2.583	2.729		
	Illite; 27% clay		3.955	4.803		
	Smectite; 36% clay		4.619	4.691		
	Mixed; 49% clay		3.291	3.274		
K%_Leaf2_DAS_120	Kalonite; 3% clay		4.006	3.678		
	Kalonite; 9% clay		2.655	3.597		
	Illite; 27% clay		5.003	5.205		
	Smectite; 36% clay		4.881	4.774		
	Mixed; 49% clay		3.219	3.380		
K%_Leaf3_DAS_180	Kalonite; 3% clay		1.594	1.821		
	Kalonite; 9% clay		2.019	2.993		
	Illite; 27% clay		4.976	4.338		
	Smectite; 36% clay		4.076	4.598		
	Mixed; 49% clay		3.119	3.098		
Time	Clay	Potassium	100	150		
K%_Leaf1_60DAS	Kalonite; 3% clay		4.041	4.618		
	Kalonite; 9% clay		2.916	4.121		
	Illite; 27% clay		5.642	5.413		
	Smectite; 36% clay		5.132	5.758		
	Mixed; 49% clay		3.772	3.549		
K%_Leaf2_DAS_120	Kalonite; 3% clay		3.906	4.501		
	Kalonite; 9% clay		3.813	3.785		
	Illite; 27% clay		5.362	5.617		
	Smectite; 36% clay		4.660	6.859		
	Mixed; 49% clay		3.835	4.103		
K%_Leaf3_DAS_180	Kalonite; 3% clay		2.128	2.641		

		Kalonite; 9% clay	2.458	3.090	
		Illite; 27% clay	4.263	4.775	
		Smectite; 36% clay	4.463	4.916	
		Mixed; 49% clay	3.274	3.408	
	Time	Clay	Potassium	200	250
K%_Leaf1_60DAS		Kalonite; 3% clay	5.382	5.378	
		Kalonite; 9% clay	3.898	3.112	
		Illite; 27% clay	4.578	5.350	
		Smectite; 36% clay	4.999	4.921	
		Mixed; 49% clay	3.652	3.946	
K%_Leaf2_DAS_120		Kalonite; 3% clay	5.193	4.641	
		Kalonite; 9% clay	3.867	3.952	
		Illite; 27% clay	5.854	5.732	
		Smectite; 36% clay	7.074	5.401	
		Mixed; 49% clay	4.207	4.099	
K%_Leaf3_DAS_180		Kalonite; 3% clay	2.867	3.064	
		Kalonite; 9% clay	2.942	3.459	
		Illite; 27% clay	4.983	4.920	
		Smectite; 36% clay	4.692	3.953	
		Mixed; 49% clay	2.504	3.805	

Standard errors of differences of means

Table	Time	Clay	Potassium	Time Clay
rep.	90	54	45	18
s.e.d.	0.0992	0.1658	0.1817	0.2456
d.f.	102.58	58	58	154.55
Except when comparing means with the same level(s) of				
Clay				0.2218
d.f.				102.58

Table	Time Potassium	Clay Potassium	Time Clay Potassium
rep.	15	9	3
s.e.d.	0.2690	0.4062	0.6015
d.f.	154.55	58	154.55
Except when comparing means with the same level(s) of			
Potassium	0.2430		
d.f.	102.58		
Clay.Potassium			0.5433
d.f.		102.58	

Appendix 7.11: Chapter 7 (K pot trial) root statistical analysis

Analysis of variance

Variate: K%_Rootfinal

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.08650	0.04325	2.54	
Block.*Units* stratum					
Clay	4	3.00488	0.75122	44.04	<.001
Potassium	5	0.06060	0.01212	0.71	0.618
Clay.Potassium	20	0.58843	0.02942	1.72	0.055
Residual	58	0.98931	0.01706		
Total	89	4.72972			

Message: the following units have large residuals.

Block 1 *units* 2	-0.460	s.e. 0.105
Block 2 *units* 15	0.271	s.e. 0.105

Tables of means

Variate: K%_Rootfinal

Grand mean 1.222

Clay	Kalonite; 3% clay	Kalonite; 9% clay	Illite; 27% clay			
	0.977	1.071	1.400			
Clay	Smectite; 36% clay	Mixed; 49% clay				
	1.450	1.209				
Potassium	0	50	100	150	200	250
	1.205	1.195	1.198	1.230	1.271	1.230
Clay	Potassium	0	50	100	150	200
Kalonite; 3% clay		0.870	0.914	1.094	0.904	0.993
Kalonite; 9% clay		0.988	1.102	1.085	1.099	1.135
Illite; 27% clay		1.532	1.374	1.335	1.258	1.482
Smectite; 36% clay		1.405	1.526	1.389	1.560	1.502
Mixed; 49% clay		1.231	1.061	1.090	1.328	1.239
Clay	Potassium	250				
Kalonite; 3% clay		1.090				
Kalonite; 9% clay		1.016				
Illite; 27% clay		1.422				
Smectite; 36% clay		1.321				
Mixed; 49% clay		1.302				

Least significant differences of means (5% level)

Table	Clay	Potassium	Clay Potassium
rep.	18	15	3
d.f.	58	58	58
l.s.d.	0.0871	0.0955	0.2135

Stratum standard errors and coefficients of variation

Variate: K%_Rootfinal

Stratum	d.f.	s.e.	cv%
Block	2	0.0380	3.1
Block.*Units*	58	0.1306	10.7

Fisher's unprotected least significant difference test

Clay

	Mean	
Kalonite; 3% clay	0.977	a
Kalonite; 9% clay	1.071	b
Mixed; 49% clay	1.209	c
Illite; 27% clay	1.400	d
Smectite; 36% clay	1.450	d

Appendix 8.1: Chapter 8 segmented regression analysis for the determination of a breakpoint for acid saturation

Regression analysis

Response variate: Relative_yield_%
Fitted terms: Constant, Asat_%

Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	1736.	1736.1	7.60	0.007
Residual	126	28767.	228.3		
Total	127	30503.	240.2		

Percentage variance accounted for 4.9
 Standard error of observations is estimated to be 15.1.

Message: the following units have large standardized residuals.

Unit	Response	Residual
96	100.0	2.70
108	12.1	-3.27

Message: the residuals do not appear to be random; for example, fitted values in the range 59.5 to 59.5 are consistently smaller than observed values and fitted values in the range 57.1 to 57.9 are consistently larger than observed values.

Message: the following units have high leverage.

Unit	Response	Leverage
21	46.9	0.059
36	39.1	0.043
55	23.8	0.043
103	41.0	0.063
107	50.9	0.059
122	23.8	0.051

Estimates of parameters

Parameter	estimate	s.e.	t(126)	t pr.
Constant	62.34	2.28	27.37	<.001
Asat_%	-0.403	0.146	-2.76	0.007

```
67 R2LINES [PRINT=summary,model,estimates; PLOT=lines; HORIZONTAL=left;
CIPROBABILITY=0.95;\
68 NGRID=30] Relative_yield_%; X=Asat_%
```

Fit of straight- and horizontal-line model

Horizontal line is on left

Nonlinear regression analysis

Response variate: Relative_yield_%
Nonlinear parameters: Breakpoint_X
Model calculations: Twolines[1], Twolines[2]
Fitted terms: Breakpoint_Y, Slope_1

Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.
Regression	3	422160.	140719.9	631.53
Residual	125	27853.	222.8	
Total	128	450013.	3515.7	

Percentage variance accounted for 7.2

Standard error of observations is estimated to be 14.9.

Message: the following units have large standardized residuals.

Unit	Response	Residual
96	100.0	2.75
108	12.1	-3.13

Estimates of parameters

Parameter	estimate	s.e.
Breakpoint_X	21.000	0.379
* Linear		
Breakpoint_Y	58.91	1.41
Slope_1	-1.379	0.403

X value at intersection of lines

X value 21.0000, approximate s.e. 0.3787
95% confidence interval (2.791, 29.67)

Appendix 8.2: Estimated gross margin analysis for root chicory at R 1 200 t⁻¹ in KwaZulu-Natal using fertiliser research information for a sandy loam soil under irrigation (modified from MBB Consultants, 2016)

Description	Yield (t ha ⁻¹)		
	30	40	50
Gross Income	R 36 000	R 48 000	R 60 000
Allocated costs			
Land Preparation on Contract	4 400	4 400	4 400
Slash	400	400	400
Disc	600	600	600
Plough	800	800	800
Spread fertiliser	400	400	400
Disc	600	600	600
Spray herbicide	400	400	400
Ridge	400	400	400
Plant	400	400	400
Top-dress nitrogen	400	400	400
Seed	500	500	500
Fertiliser	4 609	5 614	6 954
KCl (50%) (150 kg ha ⁻¹)	2 045	2 045	2 045
Superphosphate (8.7%) (300 kg ha ⁻¹)	1 424	1 424	1 424
Solubor (21%) (2 kg ha ⁻¹)	135	135	135
LAN. (28%)	(60N) 1005	(120N) 2010	(200N) 3350

Appendix 8.2 (contd.) : Estimated gross margin analysis for root chicory at R 1 200 t⁻¹ in KwaZulu-Natal using fertiliser research information for a sandy loam soil under irrigation (modified from MBB Consultants, 2016)

	Yield (t ha ⁻¹)		
	30	40	50
Gross Income	R 36 000	R 48 000	R 60 000
R16.75 kg ⁻¹ N	178 kg LAN	536 kg LAN	714 kg LAN
Herbicide	435	435	435
Gramoxone 6 (L ha ⁻¹)	409	409	409
Wetting agent	26	26	26
Irrigation	3 216	3 216	3 216
500 mm (R3.36 mm ⁻¹)	1 680	1 680	1 680
Labour (12 days)	1 536	1 536	1 536
Weeding Labour (40 days)	5 120	5 120	5 120
Harvest	10 640	13 920	17 200
Contract	800	800	800
Labour (1 day ton ⁻¹)	3 840	5 120	6 400
Transport (R200 t ⁻¹)	6 000	8 000	10 000
Total allocated costs (R ha⁻¹)	28 920	33 205	37 825
Gross margin (R ha⁻¹)	7 080	14 795	22 175

Appendix 8.3: Gross margin analysis for various chicory yields at R1 200 ton⁻¹ wet root (MBB Consultants, 2016)

Yield targets (t ha ⁻¹)	20	30	40	50
Gross Income per ha (R)	R 24 000.00	R 36 000.00	R 48 000.00	R 60 000.00
Total Allocated Costs per ha (R)	R 23 958.00	R 26 658.00	R 29 630.00	R 32 330.00
Gross Margin per ha (R)	R 42.00	R 9 342.00	R 18 370.00	R 27 670.00

Appendix 8.4: Comparison of chicory (at R1 200 ton⁻¹ wet root) gross margin with other crops (MBB Consultants, 2016)

Crop	Irrigated yield (t ha⁻¹)	Gross income (R)	Allocated costs (R)	Gross margin (R)
Cabbage	60	93 300	53 204	40 096
Chicory	50	60 000	32 330	27 670
Green Maize	10	50 000	22 807	27 193
Butternut	20	60 000	36 605	23 395
Spinach	20	61 800	40 385	21 415
Chicory	40	48 000	29 630	18 370
Sweet Potatoes	20	59 640	45 647	13 993
Chicory	30	36 000	26 658	9 342
Chicory	20	24 000	23 958	42

Appendix 8.5: Comparison of chicory (at R 1 400 ton⁻¹ wet root) gross margin with other crops (MBB Consultants, 2016)

Crop	Irrigated yield (t ha⁻¹)	Gross income (R)	Allocated costs (R)	Gross margin (R)
Cabbage	60	93 300	53 204	40 096
Chicory	50	70 000	32 330	37 670
Green Maize	10	50 000	22 807	27 193
Chicory	40	56 000	29 630	26 370
Butternut	20	60 000	36 605	23 395
Chicory	30	42 000	26 658	15 342
Sweet Potatoes	20	59 640	45 647	13 993
Chicory	20	28 000	23 958	4 042